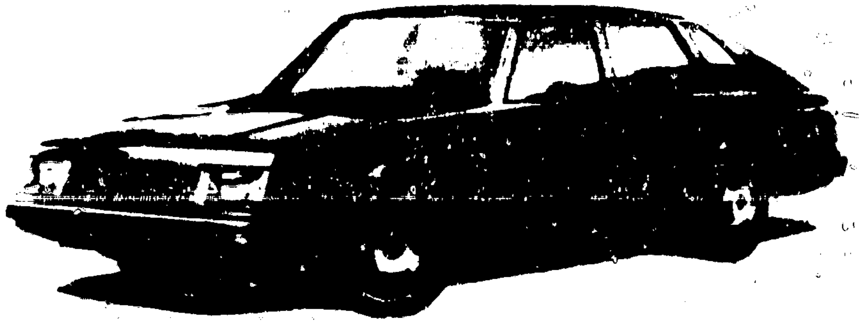
NEAR-TERM HYBRID VEHICLE PROGRAM

FINAL REPORT — PHASE I



Contract No. 955190

Submitted to

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Submitted by

General Electric Company
Corporate Research and Development
Schenectady, New York 12301

October 8, 1979

GENERAL ELECTRIC

SRD-79-134/1

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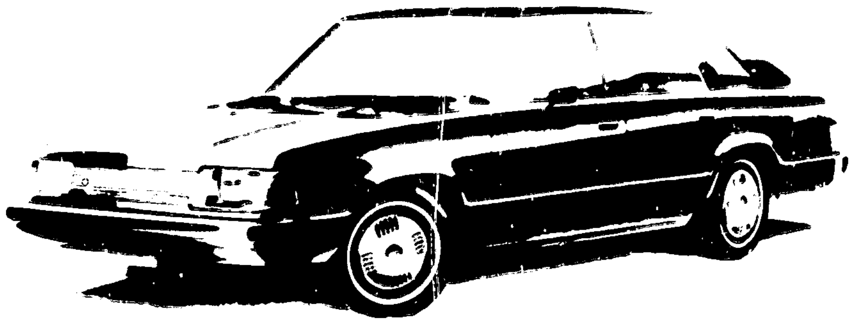

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FOREWORD

The Electric and Hybrid Vehicle (EHV) Program was established in DOE in response to the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. Responsibility for the EHV Program resides with the Office of Electric and Hybrid Vehicle Systems of DOE. The Near-Term Hybrid Vehicle (NTHV) Program is an element of the EHV Program. DOE has assigned procurement and management responsibility for the Near-Term Hybrid Vehicle Program to Jet Propulsion Laboratory (JPL).

The overall objective of the DOE EHV Program is to promote the development of electric and hybrid vehicle technologies and to demonstrate the validity of these systems as transportation options which are less dependent on petroleum resources.

As part of the NTHV Program, General Electric and its subcontractors have completed studies leading to the Preliminary Design of a hybrid passenger vehicle which is projected to have the maximum potential for reducing petroleum consumption in the near term (commencing in 1985). This work has been done under JPL Contract Number 955190, Modification 3, Phase I of the Near-Term Hybrid Vehicle Program.

This report is Deliverable Item 7, Final Report. The material included in this report summarizes all of the effort in Phase I. In accordance with Data Requirement Description 7 of the Contract, the following documents are submitted as appendices:

APPENDIX A is the Mission Analysis and Performance Specification Studies Report. This is Deliverable Item 1 and reports on the work of Task 1. It presents the study methodology; the vehicle characterizations; the mission description, characterization, and impact on potential sales; the rationale for the selection of the ICE reference vehicle; and conclusions and recommendations of the mission analysis and performance specifications studies.

APPENDIX B is a three volume set that constitutes Deliverable Item 2 and reports on the work of Task 2. The three volumes are:

- Volume I -- Design Trade-Off Studies Report
- Volume II -- Supplement to Design Trade-Off Studies Report, Volume I
- Volume III -- Computer Program Listings.

Volume I presents the study methodology; the evaluation and comparison of candidate power trains; the control strategy and the selected design concept. Volume II presents reports submitted by subcontractors on heat engines, battery power sources, and vehicle

technology along with detailed background on motors and controls. Volume III consists of listings of computer programs used in analyzing the various design options.

APPENDIX C is the Preliminary Design Data Package. This is Deliverable Item 3 and reports on the work of Task 3. It presents the design methodology, the design decision rationale, the vehicle preliminary design summary, and the advanced technology developments. Included in the Preliminary Design Data Package are five appendices which present the detailed vehicle design; the vehicle ride and handling and front structural crashworthiness analysis; the microcomputer control of the propulsion system; the design study of the battery switching circuit, the field chopper, and the batter charger; and the recent HYVEC program refinements and computer results.

APPENDIX D is the Sensitivity Analysis Report. This is Deliverable Item 8 and reports on Task 4. It presents the study methodology, the selection of input parameters and output variables, the sensitivity study results, and the conclusions of the sensitivity analysis.

The three classifications - Appendix, Deliverable Item, and Task Number - will be used interchangeably in these documents. The work accomplished on this contract, which is fully described in this report and its appendices, was performed by the Electric Vehicle Program in the Power Electronics Laboratory of General Electric Corporate Research and Development in Schenectady, New York. Subcontractors and their areas of support were:

Subcontractor	Area of Support
• ESB, Inc.	Batteries
• General Electric Space Systems Division	Heat Engines
• Professor Gene Smith, University of Michigan	Mission Analysis and Sensitivity Analysis
• Triad Services	Vehicle Design and Analysis

Other contributors to the General Electric Vehicle Program whose consultations were applicable to this study were:

Source	Area of Consultation
• Diahatsu Motor Company Ltd. (Mr. Shoji Honda)	Hybrid Vehicles
• General Electric DC Motor and Generator Department	Motors
• General Electric Ordnance System Products Department	Transmissions and other Mechanical Components
• Volkswagen AG	Heat Engines and Hybrid Vehicle Power Trains

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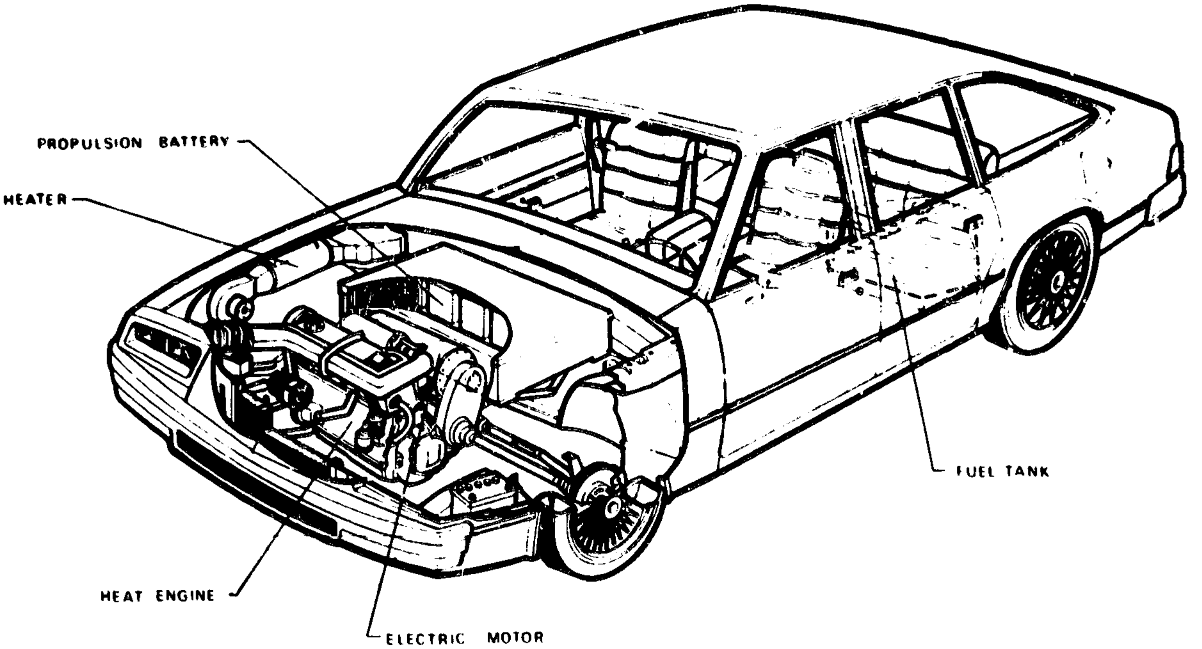

Near-Term Hybrid Vehicle, Three-Dimensional Cutaway

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Section 1

INTRODUCTION AND SUMMARY

Section 1

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

This report is Deliverable Item 7, Final Report, and is the summary report of a series which document the results of Phase I of the Near-Term Hybrid Vehicle Program. This phase of the program was a study leading to the preliminary design of a 5-passenger hybrid vehicle utilizing two energy sources (electricity and gasoline/diesel fuel) to minimize petroleum usage on a fleet basis.

The program is sponsored by the US Department of Energy (DOE) and the California Institute of Technology, Jet Propulsion Laboratory (JPL). Responsibility for this program at DOE resides with the Office of Electric and Hybrid Vehicle Systems. Work on the Phase I portion of the program was done by General Electric Corporate Research and Development and its subcontractors under JPL contract 955190.

This report presents a complete summary of the work done on Phase I, in the following manner:

- Overall summary of the Phase I activity
- Summary of the individual tasks
- Summary of the hybrid vehicle design
- Summary of the alternative design options
- Summary of the computer simulations
- Summary of the economic analysis
- Summary of the maintenance and reliability considerations
- Summary of the design for crash safety
- Bibliography

These summaries are based on and are supported by the series of task reports that were submitted as deliverable items during the contract. The task reports are being resubmitted as appendices to this Final Report. The interrelationship of appendices, deliverable items, and tasks is tabulated below:

Appendix	Deliverable Item	Task	Title
A	1	1	Mission Analysis and Performance Specification Studies Report
B	2	2	Vol. I - Design Trade-Off Studies Report
			Vol. II - Supplement to Design Trade-Off Studies Report
			Vol. III - Computer Program Listings
C	3	3	Preliminary Design Data Package
D	8	4	Sensitivity Analysis Report

1.2 OBJECTIVES

The objectives that were set forth for this effort are identified in the following subsections.

1.2.1 OVERALL DOE EHV PROGRAM OBJECTIVES

The overall objective of the DOE EHV Program is to promote development of electric and hybrid vehicle technologies and to demonstrate the validity of these systems as transportation options which are less dependent on petroleum resources.

The Near-Term Hybrid Vehicle Program is an element of the EHV Program. DOE has assigned procurement and management responsibility for the Near-Term Hybrid Vehicle Program to JPL.

1.2.2 DOE NEAR-TERM HYBRID VEHICLE PROGRAM OBJECTIVES

The DOE Near-Term Hybrid Vehicle (NTHV) Program Objectives are summarized as follows:

- Advance the state of the art in hybrid vehicles
- Show that hybrid vehicles can be

  Practical
  Energy efficient
  Safe
  Producible
  Affordable
  Functional

- Develop validated vehicle designs that can be useful candidates for the demonstration program
- Provide analytical and test methodologies and tools for general application to hybrid vehicle technology.

The NTHV Program is planned as a multiyear project of two phases:

- Phase I -- Design Trade-Off Studies and Preliminary Design
- Phase II -- Final Design and Fabrication of Test Vehicles

1.2.3 SPECIFIC PHASE I OBJECTIVES

The specific objectives of Phase I of the Near-Term Hybrid Vehicle Program are to:

- Identify missions for hybrid vehicles that promise to yield high petroleum impact,
- Characterize the single vehicle concept which satisfies the mission or set of missions that provide the greatest potential reduction in petroleum consumption,
- Develop performance specifications for the characterized vehicle concept,
- Develop, through trade-off studies, a hybrid vehicle preliminary design that satisfies the performance specifications,
- Identify technologies that are critical to successful vehicle development,
- Develop a proposal for the Phase II activities that include vehicle design, critical technology development, and vehicle fabrication.

1.3 DESCRIPTION OF MAJOR TASKS

The Phase I program was divided into discrete tasks in accordance with the contract. The work consisted of the following major tasks:

Task 1 - Mission Analysis and Performance Specification Studies

Task 2 - Design Trade-off Studies

Task 3 - Preliminary Design

Task 4 - Sensitivity Analysis

Task 5 - Proposal for Phase II

Task 6 - Phase I Documentation

Task 7 - Program Management and Integration

The work done on this program is described in subsequent sections of this report. Section 2, Summary of the Phase I Tasks, describes how the tasks interrelate and gives details of the four major tasks (Tasks 1 through 4). These sections include the specific tasks objectives, and a discussion of the methodology, and the major findings, conclusions, or recommendations. In addition, the complete reports associated with Tasks 1, 2, 3, and 4 are submitted as appendices to this report. A brief summary description of the major tasks and identification of the task reports follows.

1.3.1 TASK 1, MISSION ANALYSIS AND PERFORMANCE SPECIFICATION STUDIES

The major elements of Task 1 included the following: (1) definition of the missions or set of missions which maximize the potential for reduction of petroleum consumption by a single hybrid vehicle, (2) identification of vehicle characteristics associated with these missions, and (3) preparation of specifications defining the performance requirements which the vehicle should achieve to safely and efficiently perform the mission or set of missions identified in the mission analysis. The work done on this task is reported in its entirety in Appendix A, Mission Analysis and Performance Specification Studies Report.

1.3.2 TASK 2, DESIGN TRADE-OFF STUDIES

Task 2 included trade-off studies of alternate system configurations and components in order to arrive at a hybrid vehicle design concept which best achieves the vehicle specifications

developed in Task 1 and offers the greatest promise of reducing petroleum consumption. The work done in this task is reported in its entirety in Appendix B, Design Trade-off Studies Report, Volumes I, II, and III.

1.3.3 TASK 3, PRELIMINARY DESIGN

Task 3 carried out a preliminary design of the most promising hybrid vehicle concept identified in the Task 2 studies. It included definition of all major parameters and components, such as internal and external dimensions; all power train components; materials for body and chassis; weight breakdown by major subassemblies; projected production and life cycle costs; performance (including all categories specified in Task 1); and identification of technology development required to achieve this preliminary design. The work done on this task is reported in its entirety in Appendix C, Preliminary Design Data Package.

1.3.4 TASK 4, SENSITIVITY ANALYSIS

Task 4 carried out a sensitivity analysis which determined the impact of variations in selected parameters on the utility, the economic attractiveness, and the marketability of the hybrid vehicle. The parameters varied included travel characteristics, energy costs, hybrid vehicle lifetime, maintenance cost, and fuel economy of the Reference ICE Vehicle. The work done in Task 4 is reported in its entirety in Appendix D, Sensitivity Analysis Report.

1.3.5 TASK 5, PROPOSAL FOR PHASE II

Task 5 consisted of preparing a proposal for Phase II of the program which included a final vehicle design based upon results of Task 3 preliminary design. Subject to JPL approval of this final design, two hybrid vehicles with spares and support equipment will be fabricated in Phase II. The Phase II effort also includes testing the vehicles, delivering them to JPL, and providing field support during acceptance testing. The Phase II proposal was prepared in response to RFP JC-2-2974-305 issued by JPL on July 6, 1979. The proposal, Phase II of the Near-Term Hybrid Vehicle Program, Proposal RFP JC-2-2974-305, was submitted to JPL on August 24, 1979. It consisted of three volumes which were: Volume I - Technical Proposal; Volume II - Management Proposal; and Volume III - Cost Proposal.

1.3.6 TASK 6, PHASE I DOCUMENTATION

Task 6 consisted of preparation of monthly status reports; the separate reports for Tasks 1, 2, 3, and 4, respectively; the proposal for Phase II; and this final report for all of Phase

I. These reports have been identified where appropriate in the preceding paragraphs.

1.3.7 TASK 7, PROGRAM MANAGEMENT AND INTEGRATION

Task 7 consists of the program management and integration effort required to maintain technical and cost control and assure achievement of the Phase I objectives. This is mentioned for completeness, since it played a vital role in the successful execution of the program. It is not covered in this final report or in the technical reports which were submitted previously.

1.4 SUMMARY OF PHASE I PROGRAM RESULTS

The completed Phase I Program has resulted in the Preliminary Design of a hybrid vehicle which fully meets or exceeds the requirements set forth in JPL Contract 955190. This work is fully documented as discussed in Section 1.3. Highlights of the preliminary design are presented in the following sections along with the alternative options which were considered.

1.4.1 PRELIMINARY DESIGN SUMMARY

There are many aspects of the preliminary design that are considered important. The following sections discuss those deemed to be most relevant.

1.4.1.1 General Layout and Styling

The general characteristics of the vehicle layout and chassis are:

- Curb weight
  - 1786 kg (3930 lb)
- Body style
  - Four-door hatchback
  - Drag Coefficient - 0.40
  - Frontal area - 2.0 m^2 (21.5 ft^2)
- Chassis/Power Train Arrangement
  - Front wheel drive
  - Complete power train, including the batteries, in front of firewall
  - Fuel tank under rear seat
- Baseline ICE Vehicle
  - 1979 Chevrolet Malibu

A three-dimensional cutaway of the hybrid vehicle indicating the placement of the power train is shown in Figure 1.4.1-1. Note that the complete hybrid power train is located in front of the firewall with no intrusion into the passenger compartment. The drive train consists of an 80 hp (peak) 1.6 liter fuel-injected gasoline engine, a 45 hp (peak) separately excited dc motor, an automatically shifted transmission, clutches, and accessory drive components. An artist's rendering of the vehicle styling is shown

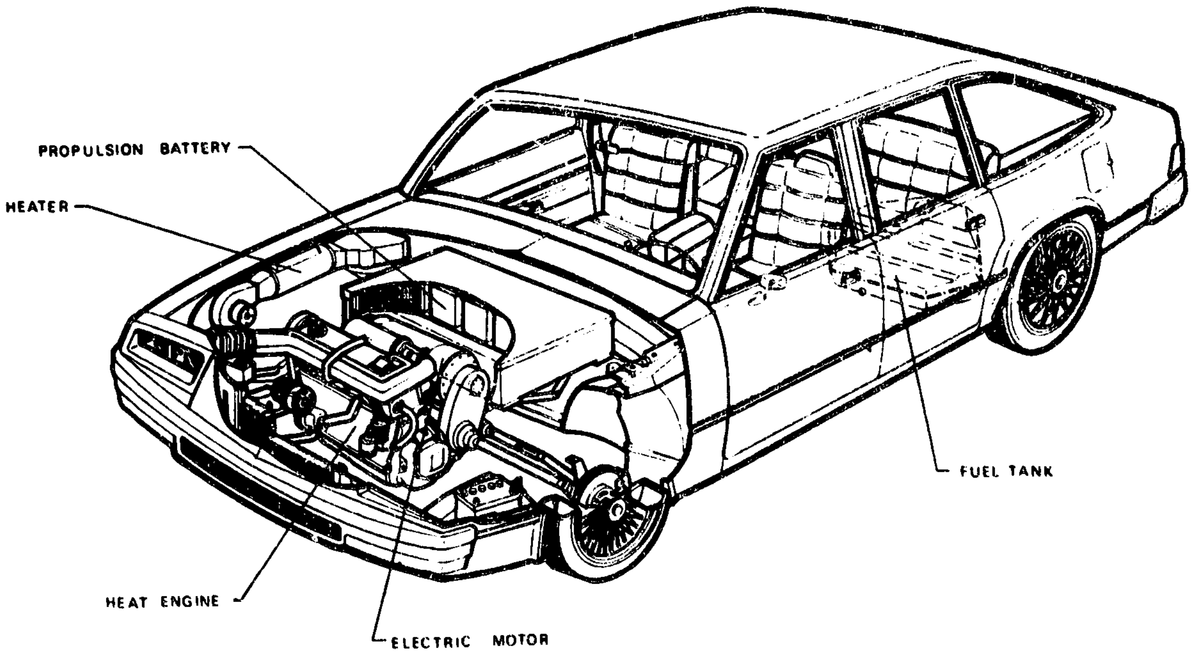


Figure 1.4.1-1. Near-Term Hybrid Vehicle, Three-Dimensional Cutaway

in Figure 1.4.1-2. A four-door hatchback body type was selected because it maximizes the all-purpose character of the five-passenger vehicle and hence its marketability.

1.4.1.2 Energy Use

The primary goal of the hybrid vehicle program is to conserve petroleum. The vehicle which was designed in Phase I offers great promise in meeting this goal. Figure 1.4.1-3 shows that the fuel economy of the near-term hybrid vehicle is in excess of 60 mpg for trips of 30 miles or less. Figure 1.4.1-4 illustrates the petroleum fuel enery savings when compared to the Reference ICE Vehicle (1985 model). The total energy used (fuel and electricity, including generating efficiency) by the near-term hybrid vehicle is about 5% less than the Reference ICE Vehicle.

1.4.1.3 Cost Considerations

A second important goal of the hybrid vehicle design was to be competitive with the Reference ICE Vehicle in first cost and equal or lower in total ownership cost. The hybrid vehicle sticker price is estimated at $7600 in 1978 dollars, versus $5700 in 1978 dollars for the Reference ICE Vehicle. The ownership cost advantage of the hybrid vehicle can be seen in Figures 1.4.1-5 and 1.4.1-6 which show the ownership cost and net annual dollar savings as a function of gasoline price. The hybrid vehicle has the advantage of lower ownership cost as gasoline prices exceed $1/gal.

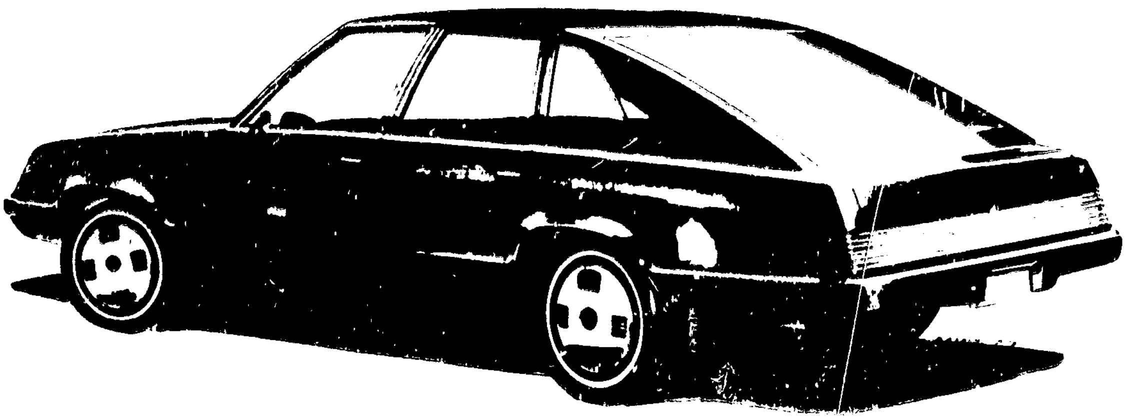
1.4.1.4 Major Features of the Design

The major features of the design are summarized in this subsection. In Section 3 of this Final Report, the Vehicle Performance characteristics and the Energy Consumption Measures are given in the format provided by JPL. These features are discussed in the following sections.

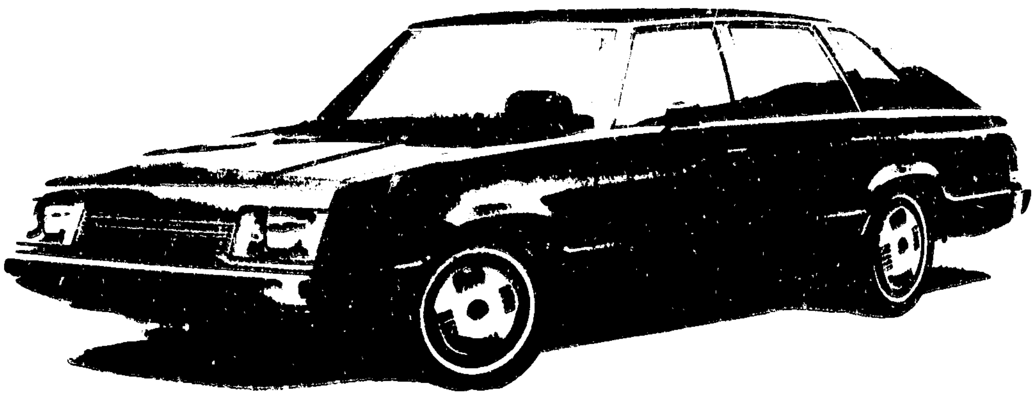
1.4.1.4.1 Vehicle Design - The Vehicle Design features which are considered to be of greatest importance in reducing technical risk while meeting JPL performance requirements are:

(1) A microprocessor-based controller evolved from vehicle and electrical system controls developed by GE/CRD for the Near-Term Electric Vehicle Program and the highly-refined electronic engine controls developed by VW,

(2) A drive motor based on the motor developed by GE DC Motor and Generator Department for the Near-Term Electric Program,



Left Rear Quarter View



Left Front Quarter View

Figure 1.4.1-2. Artist's Rendering of the Hybrid Vehicle

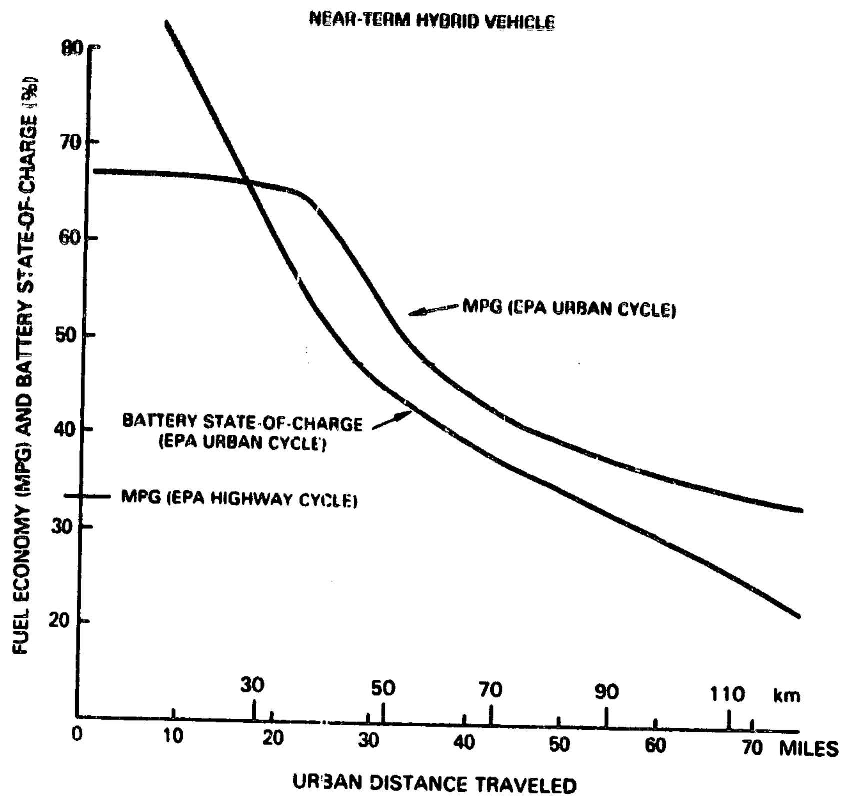


Figure 1.4.1-3. Battery State-of-Charge and Fuel Economy for Urban and Highway Driving

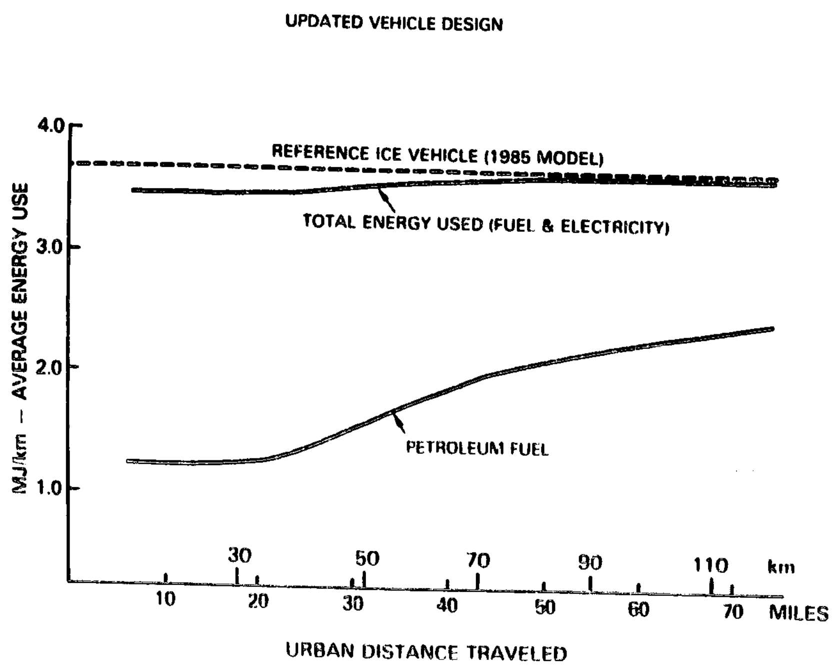


Figure 1.4.1-4. Total Energy and Petroleum Fuel Usage in Urban Driving for the Near-Term Hybrid Vehicle

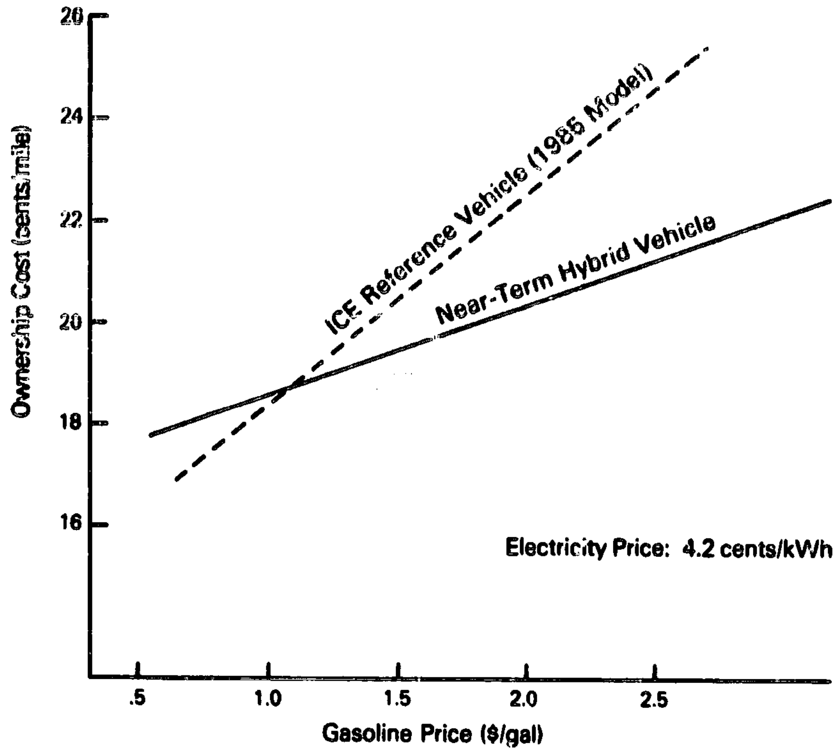


Figure 1.4.1-5. Ownership Cost as a Function of Gasoline Price

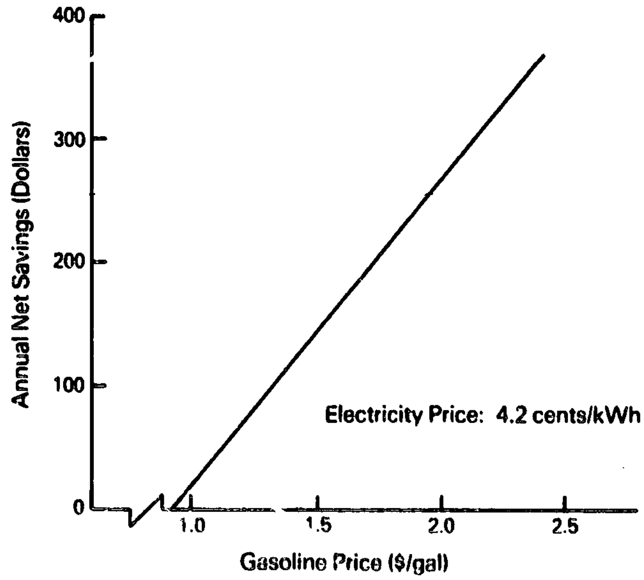


Figure 1.4.1-6. Annual Net Dollar Savings as a Function of Gasoline Price

(3) A battery subsystem based on the battery developed by Globe-Union for the Near-Term Electric Vehicle Program and recent developments on electrolyte circulation for the Argonne National Laboratory Near-Term Battery Program,

(4) An engine based on a VW production engine, VW advanced studies and experiments on emissions, and VW proprietary work on quick start for on/off engine operation,

(5) A vehicle subsystem design by Triad Services based on the extensive use of major components from late model production cars with a minimum of new design,

(6) A hybrid propulsion subsystem (including the battery) which is packaged entirely under the hood with no intrusion into the passenger compartment or the luggage compartment.

(7) Performance analysis models and computer programs which have been developed and validated by GE/CRD for second-by-second analysis of system performance during the Phase I Hybrid Vehicle Program.

1.4.1.4.2 Power Train Design

The Hybrid Vehicle designed in this study has the following power train characteristics:

(1) The propulsion subsystem is a parallel configuration in which the heat engine and the electric motor can deliver mechanical torque to the drive shaft, either together or individually.

(2) The electric motor (45 hp peak) will be used primarily for urban driving with moderate accelerations, speeds below 30 mph, ranges of less than 35 miles, and regenerative braking at all speeds.

(3) The heat engine (80 hp peak) will be used primarily for highway driving at speeds above 30 mph and to augment the electric motor for fast accelerations at lower speeds.

(4) The electric motor will augment the heat engine for fast accelerations at high speed and to maintain speed on steep grades.

(5) The engine can power the vehicle and drive the motor as a generator to recharge the batteries for extended range in urban areas. It can also be used to recharge the battery at rest when a source of electric power is not available. This use of the engine is not recommended except when no other method of recharging is available.

(6) Either the electric motor or the heat engine can operate the vehicle with reduced performance should one of the systems be inoperative.

1.4.1.4.3 Vehicle Performance

The hybrid vehicle has the following performance characteristics:

(1) It can perform all the driving missions required of a 5-passenger family sedan.

(2) It overcomes the range and acceleration limitations of the all-electric car.

(3) It offers acceleration, cruising speed, and passenger comforts comparable to the Reference ICE Vehicle (1979 Chevrolet Malibu).

(4) It results in 35% to 70% savings in petroleum (depending on daily travel) in normal urban driving compared to the Reference ICE Vehicle.

(5) It uses significantly less total energy in urban driving for the first 30 miles of travel and essentially the same energy for daily travel in excess of 75 miles compared to the Reference ICE Vehicle.

(6) The hybrid has a first cost of $7600 in 1978 dollars compared to $5700 for the Reference ICE Vehicle. For an annual mileage of 11,850 miles, electricity costs of 4.2 ¢/kwh, and gasoline costs of $1/gal or higher, the hybrid vehicle has an ownership cost which is slightly less than that of the Reference ICE Vehicle.

1.4.2 MAJOR ALTERNATIVE DESIGN OPTIONS

A number of design options were evaluated in considerable depth before making the final decisions on the preliminary design. These are discussed in Section 4, Alternative Design Options Considered and Their Relationship to the Design Adopted.

1.4.2.1 Summary of Major Design Options Considered

The power train design options considered in depth and the ones chosen for the near-term preliminary design are listed in Table 1.4.2-1.

Table 1.4.2-1

POWER TRAIN DESIGN OPTIONS CONSIDERED IN DEPTH*

Considerations/Component	Selected Option	Principal Alternate Option
Type of Hybrid Arrangement	Parallel	Series
Use of Secondary Storage (flywheel)	No	Yes
Fraction of Peak Power from Heat Engine	2/3	-
Battery Type	ISOA Lead-Acid	Ni-Zn*
Engine Type	Fuel-injected, naturally aspirated gasoline	Turbocharged diesel*
Electric Drive Type	dc separately excited motor, field control, battery switching	dc separately excited motor with armature control and field control
Transmission Type and Gear Ratios	Automatic, gear box (3-speed)	Synchromesh gear box (4-speed)
Torque Combination	Single shaft	Power differential

* Options considered in depth means those analyzed using detailed vehicle simulations (HYVEC).

In some instances, more than one of the options evaluated were found to be attractive, and the selection of the preferred option was difficult. Those attractive options which were not selected for use in Phase II are discussed briefly in two categories, (1) technology which is not likely to be available for 1985 production but which would be monitored in case of a breakthrough, and (2) technology which is marginally near term and could be a good candidate for the Near-Term Hybrid Vehicle Program if technical uncertainties were resolved.

1.4.2.1.1 Alternative Options Which Should Be Monitored - The following options were identified which warrant monitoring during the Phase II Program:

Electric Drive

A contender for the electric drive was the ac induction motor with a pulsed-width modulated inverter. This option is attractive because of lower weight, smaller size, and higher efficiency of the motor. However, the probability of this type of system being in production in 1982, particularly at a competitive cost, is low. There is development work being done on this type of motor and inverter (ref. Appendix B - Vol. II, Section 4) and this work should be closely monitored.

Transmission

One of the attractive possibilities for improving the fuel economy of the hybrid vehicle and at the same time reducing the control complexity is the steel-belt continuously variable transmission (CVT). This type of transmission has been tested in a subcompact car by Borg-Warner, but the torque rating of that CVT was significantly lower than the torque required in the hybrid vehicle. As stated in subsection 4.8, there is little likelihood that a CVT of the proper size will be in production by 1985. This work, however, should be closely monitored.

1.4.2.1.2 Options Which Should Be Evaluated Further - The following options were identified as warranting further evaluation and development in Phase II. Such additional work was proposed in Task 5 - Phase II Proposal.

Turbocharged Diesel Engine Evaluation

Section 5.1 of Appendix C, Preliminary Design Data Package, discusses the significant improvement in fuel economy of the diesel engine powered hybrid compared with the gasoline engine powered hybrid. There is uncertainty that the diesel engine will meet the potential EPA particulate and NO_x emission standards and that the diesel engine can be operated in the on-off mode. This mode requires very fast starts under a range of engine temperature conditions. It was recommended in the Phase II proposal that a study be undertaken to evaluate engine emissions and cold starting on an engine dynamometer for operating cycles appropriate for the hybrid application.

Ni-Zn Batteries

Section 5.2 of Appendix C, Preliminary Design Data Package, discusses the significant reduction in vehicle weight and improvement in fuel economy for ranges over 30 miles that would result from the use of Ni-Zn batteries rather than the ISOA lead-acid batteries used in the preliminary design. However, there has been relatively little operating experience to date with Ni-Zn batteries in electric vehicles. Even more important, there is also uncertainty regarding their energy density and power characteristics, cycle life, and cost.

It was recommended in the Phase II Proposal that a two part development program be undertaken to furnish Ni-Zn batteries which

meet the requirements of the preliminary design. Part I of the program would be to design and fabricate a first-generation battery specifically for the hybrid application. These batteries would be evaluated and, if found suitable, Part 2 of the program would be undertaken. Part 2 would consist of design and fabrication of the second generation Ni-Zn batteries for use in the Near-Term Hybrid Integrated Test Vehicle.

1.4.3 INTERFACE COMPONENT AND SYSTEM CONTROL DEVELOPMENTS

A key feature of the hybrid vehicle designed in Phase I is that it offers excellent performance at relatively low technical risk. Design and analysis problems which are not considered high risk from a technology point-of-view but still must be solved in Phase II were identified. The approaches which would be taken to solve these problems are discussed in the Phase II Proposal. Those considerations are repeated in this section because they are not covered as a separate topic in any of the reports, yet their consideration constituted an important part of the technical effort in Phase I.

1.4.3.1 Identified Problems Requiring Development

The following important interface components and control developments have been identified:

(1) Design and fabrication of a reliable torque transfer unit for combining the electric motor and heat engine outputs for input into the transaxle/gearbox,

(2) Design and test of an automatic clutch for starting the vehicle from rest and operating it at low speeds on the electric drive,

(3) Design and test of an automatic clutch for on/off operation of the heat engine when the vehicle is in motion,

(4) Smooth and efficient blending of the electric motor and heat engine torques when both units are required to power the vehicle,

(5) Development of the detailed control strategy for all vehicle operating modes and the software to implement it in the system microcomputer,

(6) Simulation of component and power train transients on the computer,

(7) Development and debugging of the system microcomputer hardware,

(8) Development of the heat engine emission control system to meet the 1981 Federal Emission Standards during on/off operating modes of the engine,

(9) Modification of the automatically shifted gearbox using input signals from the system microcomputer,

(10) Development of the shared accessory drive system and heater/defroster/air conditioning systems compatible with the hybrid application.

1.4.3.2 Solution/Approaches to Identified Problems Requiring Development

The approaches to the solution of the design/analysis problems are discussed in the following paragraphs. These will have to be solved before the Phase II Final Design and fabrication is undertaken. Each of the design/analysis problems is treated separately.

(1) Torque Transfer Unit. The torque transfer unit, which combines the outputs of the electric motor and heat engine and transfers the resultant torque to the transaxle/gearbox must be developed. Preliminary drawings for this unit, which includes the clutch and Hy-Vo chain drive for each of the prime movers, were prepared in Phase I, Task 3.

(2) Automatic Clutch for the Electric Motor. Start-up and low-speed operation of the hybrid vehicle in the electric drive mode involves the use of a slipping clutch, much the same as a conventional ICE vehicle with a manual transmission. In the hybrid vehicle, this clutch operation should be made automatic with modulation of clutch pressure based on driver torque command (i.e., position of the accelerator pedal). The basic hardware for this clutch could be a standard automotive, dry clutch, but its control must be developed. Initial work will involve laboratory tests, but the final development should be done in a mule vehicle.

(3) Automatic Clutch for the Heat Engine. The operation of the clutch that couples and decouples the heat engine into the power train will be commanded by the system controller and should be automatic both with respect to timing and rate of engagement/disengagement. The basic hardware for this clutch will likely be a standard automotive component. Its operation will be developed with initial work done on the engine dynamometer, but the final work should be done in a hybrid test bed mule vehicle.

(4) Blending of Electric Motor and Heat Engine Torques. There are several operating modes in which the outputs of the electric motor and heat engine must be blended (i.e., power sharing). The blending involves both the phasing in of one of the prime movers when the other is already operating and also phasing out one of the prime movers when it is no longer needed. This load sharing will be done using the system controller and will involve determining the proper torque rise time, decay time, and sequencing procedure needed for smooth vehicle opera-

tion. The torque blending studies should be done in a hybrid test bed mule vehicle.

(5) Control Strategy and Software for Its Implementation. Much work has been done in Phase I on developing the control strategy for the hybrid vehicle. This work will continue in both the computer simulation studies and the mule vehicle programs. The control strategy developed will be implemented in software for both the ITV system controller and the microcomputer for the hybrid test bed mule vehicle. All of these studies and controller developments should be coordinated so that the final control strategy and software used in the ITV are thoroughly evaluated and tested. The microcomputer for the hybrid test bed mule vehicle will be programmable so that the effect of changing control strategy parameters can be determined in the vehicle.

(6) Simulation of Power Train Transients. Power train transients are important in a number of vehicle operating modes (for example, blending of torques during acceleration, braking, passing maneuvers, shifting, etc.). These transients should be studied analytically as well as on the digital and hybrid computers. The results of these studies are needed to guide the design of the clutches, shifting mechanism and logic, and system controller logic and circuits.

(7) System Microcomputer Hardware. Microcomputer hardware development is needed for both the ITV and the hybrid test bed mule vehicle (HTBM). The hardware for the HTBM must be fabricated during the early part of the program. Development of the system controller hardware for the ITV will involve building up a specially designed microcomputer system from commercially available chips, interface units, etc. The ITV microcomputer must handle all operating modes of the hybrid vehicle while the microcomputer for the HTBM can include only those modes critical to the mule program.

(8) Heat Engine Emission Control System. The emission control system for the VW 1.6 ℓ EFI-L gasoline engine utilizes a three-way catalyst and feed-back control of A/F ratio using an O_2-sensor. This is the standard emission control approach for that type of engine, but since the on/off operating mode of the engine in the hybrid application is quite different from that in the conventional ICE vehicle, some development work is needed to ensure that the hybrid vehicle will meet the 1981 emission standards. Initial studies will be done on the engine dynamometer to determine the required catalyst size, substrate, and location relative to the engine exhaust for an appropriate engine cycle for the hybrid application. Particular attention should be given to catalyst warm-up and cool-down. Data should be obtained so that the emissions calculations made using HYVEC can be validated for the various driving cycles. Emission measurements should include the effect of cold start.

(9) Shifting Automatic Gearbox. The transaxle/gearbox to be used in the mule program and the ITV will be adapted from the three-speed automatic transmission used in the General Motors "X" body cars. This gearbox is a wide-range, lightweight unit especially designed for those recently introduced cars. In the hybrid application, the gearbox is shifted on command from the system microcomputer, but the shifting mechanism and internal clutches are essentially unchanged. Some adjustments might be necessary, but they can be kept to a minimum. The high-pressure hydraulic fluid needed to shift the gears is provided from a central accumulator that will be part of the closed-centered hydraulic system. Modifications to the automatic gearbox and development of the hydraulic system will be made early in Phase II. An early version of the modified gearbox is needed for the hybrid test bed mule vehicle. After further modifications, the final design will be tested and verified in the mechanical/electric mule vehicle before releasing units for the ITV.

(10) Accessory Systems. The operation and thus the design of the accessory systems on the hybrid vehicle will be significantly different from those on a conventional ICE vehicle. For example, the heater and defroster must operate satisfactorily even when significant waste heat is not available from the heat engine. This necessitates a gasoline burner to augment waste heat from the engine. Second, the accessory drive system must permit either the heat engine or the electric motor to drive the accessories (e.g., air-conditioner, alternator, hydraulic pump) or to share the load when both the heat engine and electric motor are operating. Further, it is necessary to design the accessory systems such that they require a minimum energy to operate. This requirement leads to the use of a closed-center hydraulic system and accumulator to supply high pressure fluid to the power steering, power brakes, and transmission shift systems. Available automotive components have been identified from which the accessory systems can be built, but considerable effort will be required in Phase II to design and test them.

1.5 ORGANIZATION OF THE FINAL REPORT

The remainder of this report is organized to be consistent with the Data Requirement Description 7 in the contract. References to the Task reports given in the appendices are made where appropriate. A short statement is made in each section to relate the work discussed to the Data Requirement Topic and to the proper Task and Appendix.

Section 2

SUMMARY OF PHASE I ACTIVITY

Section 2

SUMMARY OF PHASE I ACTIVITY

2.1 INTRODUCTION

A summary of all Phase I activities is presented in this section. It is structured around Tasks 1, 2, 3, and 4. For each task the objectives are given, the methodology is discussed, and the findings, conclusions, or recommendations are presented. The material describing the work in each task is summarized from the appropriate appendix which is referenced. The Near-Term Hybrid Vehicle Program, Phase I, was divided into five tasks:

Task 1 - Mission Analysis and Performance Specification Studies

Task 2 - Design Trade-off Studies

Task 3 - Preliminary Design

Task 4 - Sensitivity Analysis

Task 5 - Proposal for Phase II

A flowchart of the Phase I activities is shown in Figure 2.1-1. As indicated in the figure, Tasks 1, 2, 3, and 5 were conducted in sequence with the output of one task being used as input to the next one. Task 4 was conducted concurrently with Task 3. Formal documentation was prepared at the conclusion of each task. The task reports for Tasks 1, 2, 3, and 4 are included under separate cover.

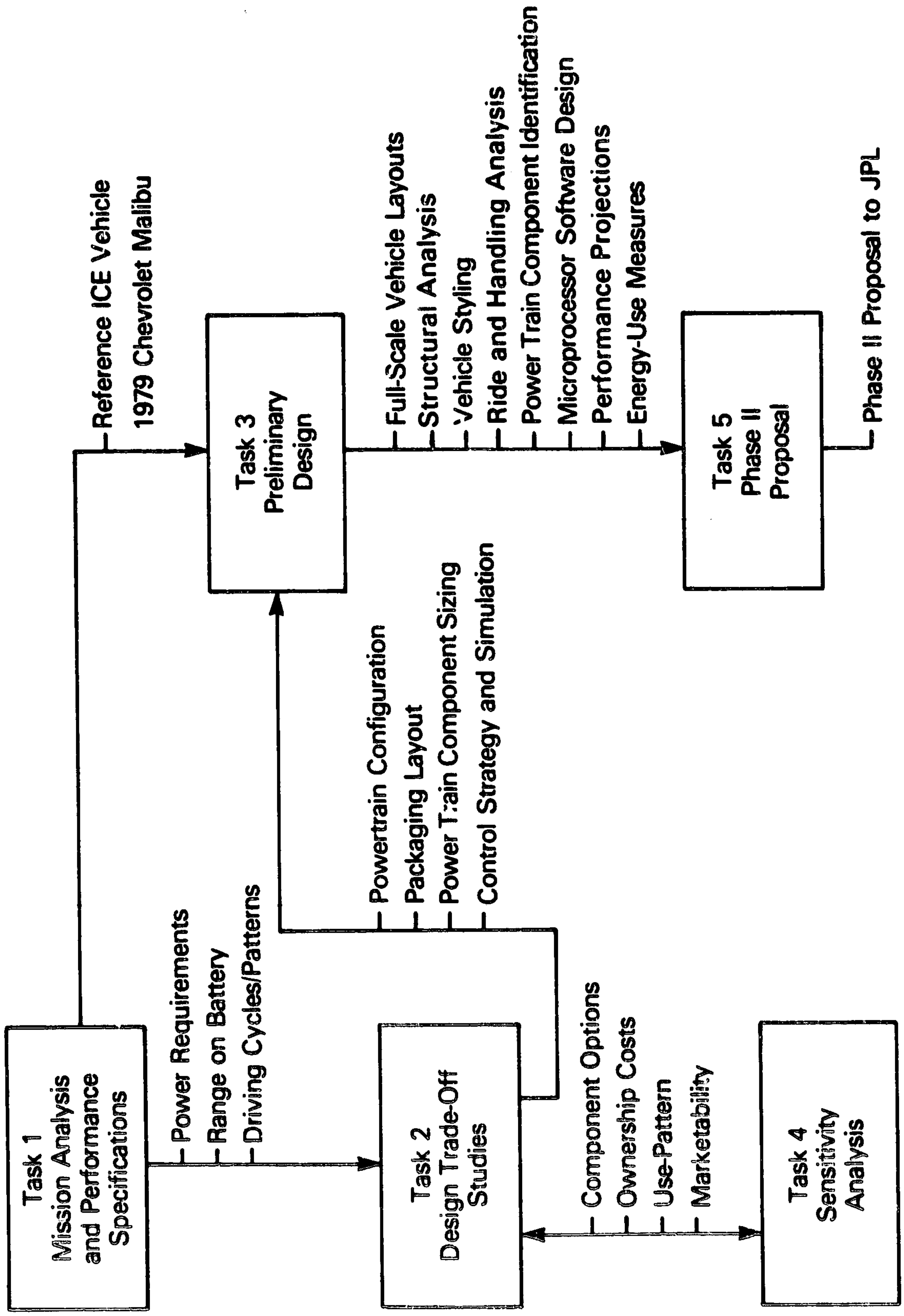


Figure 2.1-1. Phase I Activities Flowchart

2.2 TASK 1 - MISSION ANALYSIS AND PERFORMANCE SPECIFICATION STUDIES SUMMARY

This subsection summarizes the work on Task I which is given in Appendix A, Mission Analysis and Performance Specification Studies.

2.2.1 OBJECTIVES

The major objectives of the Task I study were to

- Characterize ICE vehicles in terms of weight, fuel economy, and performance,
- Characterize the use patterns of automobiles for various mission combinations,
- Determine the power requirement and electric range of the hybrid vehicle,
- Select and characterize the 1985 Reference ICE Vehicle.

2.2.2 METHODOLOGY

In the present study, passenger cars were categorized by size and passenger capacity. Four size classes were defined: small, compact, mid-size, and full size. Vehicle weight for each size class was estimated but was not used in defining the size class. Vehicle performance specifications were examined in terms of

- Top Speed
- Acceleration
- Gradability
- Low- and High-Speed Passing Capability

Performance (acceleration) required for safe operation was differentiated from performance required for ready acceptance in the marketplace. Performance requirements for the 1985 cars were then estimated based primarily on safe operation. Performance specifications for the hybrid/electric vehicle were determined and compared to the minimum requirements specified in Exhibit 1 of the contract (see Figure 2.2.2-1).

Projected characteristics of conventional ICE passenger cars were collected and examined. The characteristics of particular interest were:

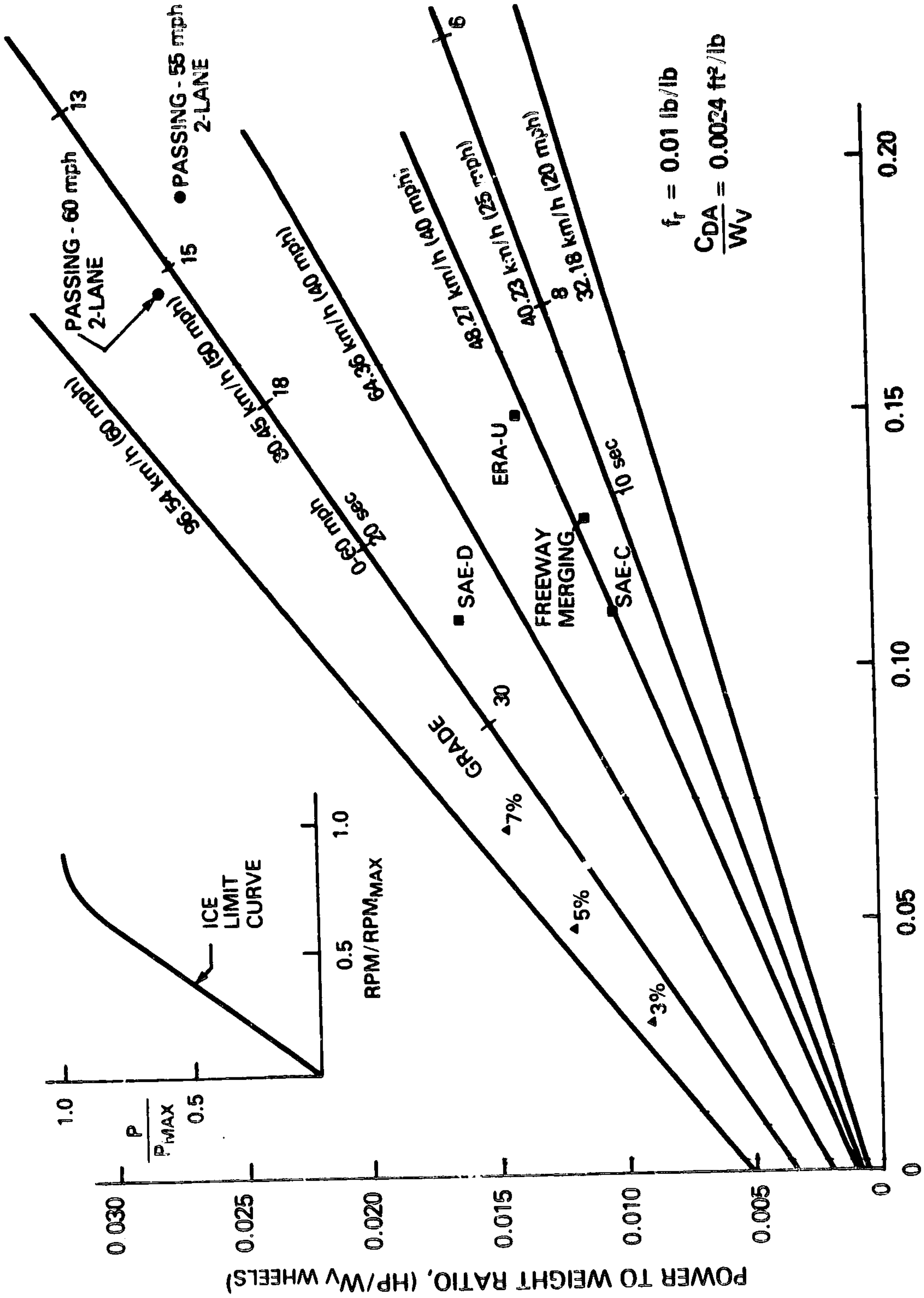


Figure 2.2.2-1. Power-to-Weight Ratio Requirements

- Exterior Dimensions
- Curb Weight
- Fuel Economy
- Exhaust Emission Standards

Data were correlated for the 1978 models and projected for 1985. The EPA urban and highway driving cycles were assumed to be representative of urban and highway driving in 1985 and were used to determine vehicle composite fuel economy for the conventional cars (see Figure 2.2.2-2). The 1977 sales mix of the four size classes was used as the basis for the 1985 sales mix in order to target the size class for the hybrid/electric vehicle (see Table 2.2.2-1).

2.2.2.1 Methodology for Mission Description and Characterization

In order to assess the effects of mission analysis on hybrid/electric vehicle design and marketability, local and regional car use was studied. Two regions were considered:

- Inside Standard Metropolitan Statistical Areas (SMSAs)
- Outside Standard Metropolitan Statistical Areas (SMSAs)

Data sources used include (1) national census surveys, (2) national transportation use-pattern surveys, and (3) car registration statistics. It was assumed that the sales mix by size class would be about the same during the next decade even though the actual size of the cars will be smaller in the future than at present.

The use pattern of the automobile varies over a wide range in terms of trip length, trip frequency, and trip purpose. Four general categories of trip purpose are defined:

- Earning a Living (Work Travel)
- Family Business
- Civic, Educational, or Religious
- Social or Recreational

The last three trip purposes were consolidated and called Personal Business. Use patterns of automobiles were characterized in terms of regular travel (e.g., work travel) and random travel (e.g., personal business). Mission sets were then described in terms of both random and nonrandom trips. A total of eight mission sets were specified and analyzed (four each for travel inside SMSAs and outside SMSAs).

Table 2.2.2-1

FUEL USE BY SIZE CLASS IN 1985

Size Class	Sales Mix %	Iw, lb	Composite mpg	Fraction of Fuel Used
Small	23.9	1900	43.8	0.16
Compact	23.3	2300	34.5	0.198
Mid-Size	24.3	2900	26.0	0.274
Full-Size	27.6	3500	22.0	0.367
				0.999

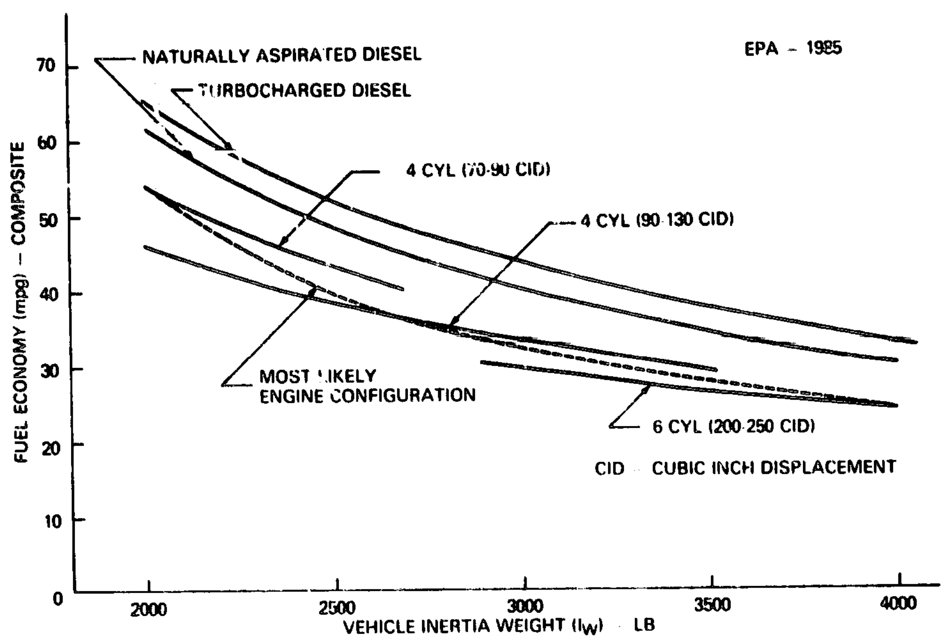


Figure 2.2.2-2. Projected 1985 Composite Fuel Economy

Characterization of automobile travel requires the following main factors:

- Annual Mileage (statistical distributions)
- Daily Travel (statistical distribution of trip length and number)
- Driving Mode

Since data pertinent to some of these factors is very limited, considerable judgement had to be used in developing inputs for the travel analysis. In the absence of data, for example, an estimate had to be made for annual mileage versus percent automobiles. Daily travel patterns were determined when at all possible through use of the Nationwide Personal Transportation Study. A computer program was written to simulate daily travel by using a Poisson distribution and a Monte Carlo simulation. The Poisson distribution determines both the number of days per year in which a specified number of trips is taken as well as the total number of trips per year. The Poisson distribution requires as input data the average number of trips per day and the average trip length. The Monte Carlo simulation uses a random number generator to predict trip length and requires the use of distribution functions for percent trips and percent vehicle miles in terms of the trip length. The results of the Monte Carlo trip simulation are used to determine the fraction of days and vehicle miles for which a hybrid/electric vehicle having a specified "electric" range can be operated primarily on the battery. Such correlations were developed for each of the mission sets. The travel and trip statistics are summarized in Tables 2.2.2-2 and 2.2.2-3.

Driving mode is usually described by a driving cycle or a combination of driving cycles. The EPA urban (FUDC) and the EPA highway (FHDC) driving cycles were examined as the means to represent urban and highway travel. The two parts (transient and stabilized) of the FUDC are used individually and in combination to describe city and surburban trips, and the FHDC is used to describe intercity travel which is considered as trips of over 100 miles.

2.2.2.2 Methodology Used in the Selection of the Reference ICE Vehicle

In order to properly assess the hybrid/electric vehicle it is necessary to identify a conventional internal combustion engine (ICE) vehicle having the same passenger carrying capacity and performance. The criteria for selection of the Reference ICE Vehicle were:

- Passenger Capacity
- Sales Volume
- Acceleration Performance

Table 2.2.2-2

DAILY AND ANNUAL TRAVEL DISTANCES INSIDE SMSAs
FOR VARIOUS MISSIONS

Mission	Annual Distance (miles)	Daily Distance (miles) Percentile *		
		50	75	90
Personal business only				
50th percentile	3,000	20	29	39
75th percentile	4,500	25	38	49
90th percentile	6,500	32	49	66
Personal business plus work trips				
50th percentile	6,625	21	32	43
75th percentile	8,125	26	39	57
90th percentile	10,125	32	51	76
All-purpose (excluding intercity travel)				
50th percentile	6,400	34	52	69
75th percentile	9,200	52	74	99
90th percentile	11,600	>100	>100	>100
All-purpose (including intercity travel)				
50th percentile	7,000	36	61	>100
75th percentile	11,300	50	84	>100
90th percentile	17,000	70	>100	>100

*Percentiles are for vehicle miles

Table 2.2.2-3

DAILY AND ANNUAL TRAVEL DISTANCES OUTSIDE SMSAs FOR VARIOUS MISSIONS

Mission	Annual Distance (miles)	Daily Distance (miles) Percentile*		
		50	75	90
Personal business only				
50th percentile	4,400	25	38	52
75th percentile	6,500	31	49	67
90th percentile	9,300	43	64	82
Personal business plus work trips				
50th percentile	6,275	23	36	54
75th percentile	8,375	31	49	68
90th percentile	11,175	42	64	90
All-purpose (excluding intercity travel)				
50th percentile	7,300	40	62	83
75th percentile	10,600	61	90	>100
90th percentile	12,700	>100	>100	>100
All-purpose (including intercity travel)				
50th percentile	9,000	43	72	>100
75th percentile	13,700	58	>100	>100
90th percentile	20,500	84	>100	>100

*Percentiles are for vehicle miles

Selection of the Reference ICE Vehicle was directed to mid-size cars because hybrid/electric cars of that size class were judged to have the greatest potential for reducing gasoline consumption. Interior dimensional criteria noted by Consumers Union (April 1978) were used to identify several 1978/1979 model mid-size cars which would be acceptable as Reference ICE Vehicles. Fuel economy and acceleration characteristics were used for further narrowing of the list of potential Reference ICE Vehicles. The final selection of the Reference ICE Vehicle (1978/1979 Model)* was based on the availability of detailed information on the ICE vehicle which was selected.

2.2.3 CONCLUSIONS

GENERAL CONCLUSIONS AND OBSERVATIONS

The following general conclusions were formulated based on the work done on mission analysis:

(1) The statistical character of automobile use is important in determining the "electric" range of the hybrid/electric vehicle and the fraction of potential car buyers whose transportation needs would adequately be met by a specific hybrid/electric vehicle design.

(2) Statistical data on annual mileage including the relationships between annual mileage and trip length frequency along with fraction of vehicle miles in trips of specified length are important in calculating auto use statistics, but the available key input data is very limited.

(3) The auto use patterns in terms of daily travel and annual mileage are significantly different inside and outside of SMSAs, and these differences can significantly affect the selection of design range for hybrid/electric vehicles.

(4) The fraction of vehicle miles rather than the fraction of days on which the car can be operated primarily on the battery is the critical factor in selecting "electric" range.

(5) The EPA urban and highway cycles can be used to describe vehicle use, and the "stabilized" portion of the EPA urban cycle is a better representation of central city driving than the SAE J227a (B) cycle.

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*Reference ICE Vehicle (1985 Model): GM mid-size; 2600 lb curb weight; length - 185 inches, width - 73 inches; fuel economy - 28/42 EPA uncorrected, 23/33 EPA corrected; acceleration - 0-60 mph, 16 sec.

**A 65%/35% annual split between urban and highway mileage is used rather than the national average of 55/45 because owners of hybrid/electric vehciles would more likely live in or near urban areas (inside SMSAs) and thus do proportionately more urban/suburban driving than the national average.

(6) The urban/highway mileage split of 65/35 is more realistic for metropolitan areas in which hybrid/electric vehicles will be most attractive than the more customary 55/45 split.**

SPECIFIC CONCLUSIONS

(1) The Chevrolet Malibu (1978) with a V-6, 231 CID engine, a 5-passenger mid-size car made by General Motors, was selected as the Reference ICE Vehicle. The projected characteristics of the 1985 model of that vehicle are used for comparison with the corresponding characteristics of the hybrid/electric vehicle.

(2) An "electric" range of 35 to 40 miles for the hybrid/electric vehicle is needed so that at least 50% of the potential midsize car buyers would drive at least 75% of annual urban vehicle miles using the electric drive as their primary propulsion means.

(3) A 0-96 km/h (0-60 mph) acceleration time* of 16 seconds was selected for the acceleration performance specification. The critical factor in this selection was safe, high-speed passing on two-lane roads. This level of performance resulted in more than adequate gradability, freeway merging capability, and top speed.

*Acceleration performance is given in terms of 0-96 km/hr (0-60 mph) rather than 0-90 km/hr (0-50 mph) as in the contract exhibits because it conforms more closely with the current practice of automotive publications for stating conventional vehicle performance. Thus most readers would have a better feel for the performance of the hybrid vehicle relative to conventional ICE vehicles if its performance is given in terms of the 0-60 mph acceleration time.

2.3 TASK 2 - DESIGN TRADE-OFF STUDIES

This subsection summarizes the work done on Task 2 which is reported fully in Appendix B - Design Trade-Off Studies Report, Volumes I, II, and III.

2.3.1 OBJECTIVES

The major objectives of the Task 2 study were to

- Characterize the major power train components including heat engines, electric motors and controllers, batteries, transmissions and torque combination units, and microprocessors,
- Evaluate and compare various hybrid power train configurations and component combinations in terms of total vehicle weight and initial cost,
- Simulate on the computer second-by-second hybrid vehicle operation over various complex driving cycles, and
- Select a hybrid power train and packaging arrangement for detailed preliminary design in Task 3.

2.3.2 METHODOLOGY

The approach used in the Design Trade-off Studies consisted of several steps. The first step involved the synthesis of total vehicle weight and cost from the specific weights and costs of individual components for a large number of candidate configurations. In this initial screening of components and drive-line configurations, the component and vehicle energy-use characteristics were averaged over the driving cycles of interest. In this first step, a wide range of drive-line components and combinations was considered using a Hybrid Vehicle Design Program (HYVELD) for the computer calculations. The objective of the vehicle-level screening was to identify those drive-line components and arrangements which are most attractive for more detailed consideration in the next step of the screening procedure.

The second step of the trade-off study involved second-by-second simulation of the hybrid/electric vehicle designs operating over several driving cycles. This simulation required detailed modeling of the various drive-line components and the control strategy for operation of the electric and heat engine drive systems. In this second step, vehicle characteristics, such as drag coefficient, frontal area, weight, etc., were fixed. The major emphasis was to determine the effect on electricity and gasoline use of power train changes, such as battery type and weight, engine type, motor voltage control technique, and variations in control strategy. The second-by-second vehicle simulations were per-

formed using the Hybrid Vehicle Calculations (HYVEC) computer program.

The third step in the Design Trade-off Study was to determine whether attractive hybrid power train arrangements could be packaged in a five-passenger car and if so, what were the primary considerations in comparing one power train layout to another.

2.3.2.1 Power Train Components and Configurations Considered

There is a myriad of possible hybrid/electric power train configurations and components which could be considered in design trade-off studies. Hence, some technical judgment was used at the outset of the study to reduce the contenders to a manageable number. For instance, the following generic hybrid arrangements were considered and then excluded:

- Electric drive through individual wheel-mounted motors
- The split power train in which one set of wheels is driven by the heat engine and the second set by the electric motor

Wheel-mounted motors were excluded because it was felt that for passenger-car size vehicles such motors are collectively less efficient, heavier, and more expensive than a single motor of the same combined horsepower. The split power train arrangement was ruled out because the control of such a system when there is power sharing between the heat engine and electric drives would present great difficulty with respect to flexibility and smoothness. In addition, the split power train arrangement is inherently heavier and more expensive than single drive shaft configurations.

The hybrid power train configurations and components considered in the present trade-off studies are listed in Table 2.3.2-1. As indicated in the table, both series and parallel configurations were analyzed in the first screening step, and a number of candidate components were studied for each function in the drive line. The effect of vehicle range and power-to-weight ratio on the relative attractiveness of the various component candidates from both the vehicle weight and cost points-of-view were investigated using the HYVELD computer program.

2.3.2.2 Component Characterization

In order to perform the trade-off studies it was necessary to characterize each of the components in Table 2.3.2-1. The degree of detail required for each component depended on whether it was included only in the vehicle level (first step) screening

or in both the vehicle level and second-by-second simulation screenings. For the initial screening, each component was characterized in terms of specific weight (lb/kW) and specific cost ($/kW). For the second-by-second simulations, detailed characterization of the components was required including efficiencies (and/or losses) over the complete operating range (power and speed) of the component. For the batteries it was necessary to obtain charge/discharge characteristics over a wide range of charge/discharge currents. For the most part, the components were characterized using data taken on existing hardware. Extensive characcerization data for each of the power train components is given in Appendix B (Volume I, Section 3).

In order to synthesize the power train, it is necessary to specify a number of vehicle characteristics and the degree of power sharing between the heat engine and electric drive systems. For the hybrid vehicle design calculations using HYVELD, the vehicle characteristics required are baseline chassis weight, payload, energy consumption per ton-mi, fraction of the energy from heat engine, and the performance parameters -- power-to-weight ratio and range on electricity. The power sharing between the heat engine and electric drive systems is specified in terms of the fraction of the peak power attainable from each drive system. The efficiency of the drive-line is specified as a single value averaged over the driving cycles of interest. As noted previously, the effect of the vehicle and power train specifications on the attractiveness of the various components is of particular importance.

2.3.2.3 Methodology for the Evaluation and Comparison of Candidate Power Trains

During the initial screening of the candidate hybrid/electric power trains, comparisons were made in terms of total vehicle weight, initial and operating costs, break-even gasoline price, and total energy used. These comparisons were made for fixed baseline vehicle chassis weight and vehicle performance specifications. The vehicles utilizing hybrid/electric power trains were also compared with the 1985 model of the Reference ICE Vehicle and an all-electric car having similar utility to a car owner. For all of these comparisons, economic factors such as interest rate, discount rate, finance period, payback period, inflation rate, etc. were held constant. In addition, the fuel economy of the Reference ICE Vehicle was fixed. Complete lists of the design and economic factors which were varied or held constant in the initial screening study are given in Table 2.3.2-2.

Candidate power trains included in the second-by-second simulation studies were compared in terms of range primarily on battery-stored electricity, fuel economy (mpg), heat engine emissions, and energy use. These comparisons were made for urban/surburan, highway, and intra-city driving using appropriate combinations of the Environmental Protection Agency's urban and highway cycles and the SAE J227a Schedule B cycle. In addition, the

Table 2.3.2-1

HYBRID POWER TRAIN CONFIGURATIONS AND COMPONENTS
CONSIDERED IN THE DESIGN TRADE-OFF STUDY

<u>General Power Train Arrangements</u>

1. Series
2. Parallel

<u>Heat Engines</u>

1. Fuel-injected Gasoline (naturally aspirated)
2. Diesel (naturally aspirated and turbocharged)
3. Uniform Charge Rotary
4. Single-shaft Gas Turbine
5. Stirling

<u>Transmission/Clutches</u>

1. Power Addition with Differential Action
2. Multi-speed Shifted Gearbox with Clutch
3. Torque Converter with Lock-up
4. Continuously Variable Transmission (CVT)

<u>Electric Drives</u>

1. DC Separately Excited with or without Armature Control
2. AC Induction with Pulse-width Modulated Inverter

<u>Batteries</u> (Primary Storage)

1. Lead-acid
2. Ni-Zn
3. Ni-Fe
4. LiAl-FeSx

<u>Secondary Storage</u>

1. Flywheel
2. Lead-Acid Batteries

Table 2.3.2-2

VEHICLE AND ECONOMIC FACTOR INPUT PARAMETERS FOR THE DESIGN TRADE-OFF CALCULATIONS

Hybrid/Electric Design Parameter	
Baseline Chassis Weight	*
Payload Weight	*
Power-to-weight Ratio	
Range (Design) - All-electric	
Range (Design) - Hybrid	
Electric Drive-line Efficiency	
Cost of Additional Chassis Weight	*
Weight Propagation Factor	*
Miles Traveled per Year	*
Fraction of Miles in City	*
Energy Consumption in City (kWh/ton-mi)	*
Energy Consumption on Highway (kWh/ton-mi)	*
Fraction of Energy from Engine in City	*
Fraction of Energy from Engine in Highway	*
Price of Electricity	*
Specific Cost of Motor/Generator ($/kW)	
Specific Cost of Generator ($/kW)	
Specific Cost of Controller ($/kW)	
Specific Weight of Motor/Generator ($/lb)	
Specific Weight of Generator ($/lb)	
Specific Weight of Controller ($/lb)	
Average Engine bsfc in City	*
Average Engine bsfc on Highway	*
Time for Sustained Power from the Flywheel	*
Conventional Vehicle Design Parameters	
Power-to-weight Ratio	
Specific Weight of Engine	
Specific Weight of Transmission	
Specific Cost of Engine	
Specific Cost of Transmission	
Fuel Economy in City	*
Fuel Economy on Highway	*
Consumer Cost	*
Price of Gasoline	*
Maintenance Cost per Mile	*
Economic Factors	
Discount Rate	*
Inflation Rate	*
Interest Rate	*
Payback Period	*
Finance Period	*
Tax Rate	*
Sales Tax	*

*Input Parameters Held Constant in Vehicle Synthesis Calculations

0-60 mph and 40-60 mph acceleration times obtained for the various candidate hybrid power trains were compared.

2.3.2.4 Vehicle-Level Power Train Layout Considerations

The results of the design trade-off studies yielded the power ratings of the heat engine and electric drive systems and the weight of the batteries needed to meet the vehicle performance and range requirements set forth by the Mission Analysis (Task 1). In addition, the trade-off studies identified particular components, such as heat engines, electric motors, and batteries, which are prime candidates for use in the Preliminary Design (Task 3). In order to investigate various options for packaging power train components of the required size into a five-passenger car, preliminary vehicle layouts were made using the 1979 Chevrolet Malibu (chassis and interior seating arrangement) as the baseline design. Various placements of the motor, engine, and batteries were made including front-and-rear-wheel drive and fore-and-aft-positioning of the batteries. These layouts formed the basis for trade-off considerations involving crashworthiness, service accessibility, handling, vehicle weight, and ease of battery maintenance.

2.3.2.5 Control Strategy and Vehicle Operation on Various Driving Cycles

Selection and evaluation of power train components must include careful consideration of the control strategy to be used. The control strategy involves coordinating use of the heat engine and electric drive systems. The power and speed requirements of the vehicle must be matched to the capabilities of the engine and motor. Power matching is accomplished by means of a transmission and/or power combination differential. The control strategy should be self-adaptive to varying levels of battery charge and rates of acceleration and deceleration. In addition, the control parameters for the various components should be easily sensed and used as inputs to the system controller. All of these aspects of developing and implementing a control strategy for the efficient, flexible, and smooth operation of the hybrid/electric power train were considered in the trade-off studies.

2.3.3 MAJOR FINDINGS

The major findings* from the Design Trade-Off Studies are:

(1) The parallel configuration with a 60/40 split between peak power of the heat engine and electric drive systems is near-optimum from the standpoints of vehicle weight, ownership cost, and energy usage (fuel and electricity).

*Detailed results of the design trade-off studies are given in Appendix B (Vol. I, Sections 5 and 8).

(2) Based primarily on economic considerations, a dc electric drive system utilizing a separately excited motor with field control and battery switching was selected for the Near-Term Hybrid Vehicle.

(3) The prime heat engine candidates are a fuel-injected gasoline engine and a turbocharged diesel. Both engines are 1.6 ℓ in displacement and develop about 80 hp. The diesel engine yielded 25 to 30% better fuel economy in the hybrid application than the gasoline engine, but technology does not currently exist to reduce the NO_x and particulate emissions of the diesel to levels being considered by the Environmental Protection Agency for 1985 (0.2 gm/mi for particulates). The diesel also has possible cold-starting problems when used in an on/off mode.

(4) A complex control strategy involving integrated power sharing between the heat engine and the electric drive systems is required for the hybrid vehicle to have acceleration performance equivalent to a conventional ICE vehicle and at the same time high fuel economy and acceptable electric range. Implementation of the control strategy developed in the computer simulations will require the use of microprocessors in the hybrid vehicle control system.

(5) The initial hybrid vehicle simulations showed that 700 lb of ISOA lead-acid batteries yielded satisfactory electric range and vehicle acceleration performance.* The Ni-Zn batteries were found to be the most attractive for the hybrid application, but there is considerable uncertainty concerning the cycle lifetime and cost of Ni-Zn batteries in the 1982 to 1985 time period.

(6) The vehicle layout studies showed that the complete hybrid power train including the lead-acid batteries can be packaged in the engine compartment of the 1979 Chevrolet Malibu without any intrusion into the passenger compartment.

(7) The initial selling price (in 1978 dollars) of the hybrid vehicle was calculated to be about $7000 compared with $5700 for a conventional ICE vehicle of the same performance and passenger-carrying capacity.† The ownership (life cycle) cost of the hybrid was calculated to be 17.8¢/mi compared with 18.5¢/mi for the Reference Vehicle for energy costs of $1.00/gal for gasoline and 4.2¢/kWh for electricity. The lifetime of the hybrid vehicle was taken to be 12 yrs compared with 10 yrs for the conventional ICE vehicle because of the long life of the electrical components, the reduced use of the heat engine, and the improved vehicle components at 5% increase in cost.

(8) Detailed hybrid vehicle simulations showed that for the first 30 mi (the electric range of the vehicle) in urban driving,

* Battery weight was established as 770 lb during Preliminary Design.
† Selling price was modified to $7600 during Preliminary Design.

the fuel economy was 80 mpg using a gasoline engine and 100 mpg using a diesel engine. Over the first 75 mi the average fuel economy of the hybrid was 42 mpg for the gasoline engine and 55 mpg using the diesel engine. The highway fuel economy of the hybrid vehicle is slightly better than that of the Reference ICE Vehicle (1985 model). In urban driving the hybrid would save about 75% of the fuel used by the conventional vehicle and in combined urban/highway driving the fuel saving is about 50%.

2.4 TASK 3 - PRELIMINARY DESIGN

This subsection summarizes the work done on Task 3 which is fully reported in Appendix C - Preliminary Design Data Package.

2.4.1 OBJECTIVES

The major objectives of the Task 3 effort were to

- Develop a detailed preliminary design (including full-scale layouts and styling) of the hybrid vehicle using the power train arrangement and components selected in Task 2,
- Perform ride and handling and barrier crash computer simulations of the hybrid vehicle design,
- Contact potential suppliers of major power train components and refine the sizing of those components,
- Perform the preliminary design of electric drive system components, including the power electronics, battery charger, and microcomputer,
- Refine the second-by-second hybrid vehicle simulation program, and
- Determine the performance and energy-use characteristics and ownership costs for the Near-Term Hybrid Vehicle.

2.4.2 METHODOLOGY

The preliminary design activities were concerned with developing detailed designs of the vehicle and power train subsystems from the design concepts evolved in Tasks 1 and 2. The primary activities undertaken in Task 3 were the following:

- Full-scale layouts of the vehicle and power train
- Vehicle styling
- Vehicle handling and crashworthiness simulations
- System microcomputer software study
- Battery switching, field chopper, and battery charger circuit design
- Refinement of HYVEC simulation calculations.

In Task 1, the Chevrolet Malibu (mid-size GM car) was selected as the Reference ICE Vehicle. Subsequent work in Task 2 indicated that the Malibu would also be a good choice for a base vehicle from which to build/fabricate the Near-Term Hybrid Vehicle.* Hence all the preliminary design layout work in Task 3 was done using the 1979

*This vehicle is to be built by 1982 and thus must use materials and automotive components available at that time.

Malibu as the starting point for the hybrid conversion. The Malibu was extensively redesigned with only the passenger compartment, window and door mechanisms, front and side glass, and door and roof metal being used essentially unchanged from the stock Malibu. The exterior of the Malibu (front and rear) was redesigned for improved aerodynamics and a fresh new look, and the front and underbody structures and front and rear suspensions along with the power train were replaced. The conversion approach significantly reduces the cost of building/fabricating the hybrid vehicle with a minimal sacrifice in vehicle attractiveness and utility. Experience gained with the General Electric Centennial and the DOE/GE Near-Term Electric Vehicle (which were essentially from-the-ground-up designs) has indicated that those parts of the vehicle being used from the stock Malibu (interior, window and door mechanisms, etc.) were particularly expensive and troublesome in the building of the new vehicles. Hence, the approach taken in the Near-Term Hybrid Vehicle Program is to redesign only the power train, running gear, load carrying structural members, and exterior styling of the vehicle and to utilize the interior and windows/doors of the stock Malibu. The introduction of front-wheel drive, downsized luxury cars, such as the Buick Riviera and Olds Toronado, by GM has provided some of the mechanical components required in the hybrid vehicle.

At the completion of the Design Trade-Off Studies, two options were still being considered for several of the hybrid power train components. These components and the options were:

- Heat Engine - fuel injected, gasoline (VW 1.6 ℓ) or a turbocharged diesel (VW 1.6 ℓ)
- Transmission - multi-speed, automatically shifted gearbox or a steel belt, traction drive continuously variable transmission (CVT)
- Torque Combination Unit - Single shaft or power differential
- Batteries - lead-acid or Ni-Zn

In all cases it was decided to proceed in the Preliminary Design Task with the more readily available and more highly developed component and to include the alternative option in an advanced technology development category. Hence, the detailed vehicle layouts were prepared using (1) a fuel-injected gasoline engine (1.6 ℓ), (2) a multi-speed, automatically shifted gearbox, (3) a single shaft (fixed speed ratios between input/output shafts) torque combination unit, and (4) ISOA lead-acid batteries. Further discussions of the use of a turbocharged diesel engine, the steel-belt CVT, and Ni-Zn batteries in the hybrid/electric power train are included under advanced technology developments. The power differential torque combination was dropped from further consideration, because of the complexity of the control of such a unit and the belief that development of the single-shaft unit would permit adequate smoothness in power blending from the heat

engine and electric motor. The advantages of the diesel engine, CVT, and Ni-Zn batteries are significant, and they would have been included in the design except for the following disadvantages in each case: (1) diesel engine - NO_x and unregulated emissions (smoke and odor) and uncertainty regarding cold start in the on/off operating mode, (2) steel-belt CVT - uncertainty regarding the availability of a unit with desired overall speed ratio and torque capability by mid-1981, and (3) Ni-Zn batteries - uncertainty in performance, cycle life, and cost of cells available by 1981. The hybrid vehicle layout is such that the advanced-technology components can be substituted for their near-term counterparts. For example, the Ni-Zn batteries could replace the lead-acid batteries with little or no change in the rest of the electric drive system.

2.4.3 MAJOR FINDINGS/ACCOMPLISHMENTS

The major findings/accomplishments of the Preliminary Design Task were the following:

(1) Detailed vehicle layouts showed that the complete power train, including the batteries, could be packaged under the hood ahead of the firewall resulting in no intrusion into the passenger compartment.

(2) The ride, handling, and crashworthiness of the hybrid conversion were found to be comparable to those of the 1979 Chevrolet Malibu.

(3) The acceleration performance of the hybrid vehicle was calculated to be 0-30 mph in 5 seconds and 0-56 mph in 12.6 seconds.

(4) Energy-use calculations showed that the Near-Term Hybrid Vehicle* would use 41% less petroleum fuel and 5% less total energy (including electrical energy generation inefficiency) compared with the Reference ICE Vehicle in 1985 for 11,852 miles of annual driving (65% urban).

(5) The use of a turbocharged diesel and/or Ni-Zn batteries in the hybrid power train would lead to a more attractive hybrid design (25% better fuel economy and 400 lb lighter vehicle, respectively) than the baseline design which uses a gasoline engine and lead-acid batteries.

(6) The use of a steel-belt CVT in the hybrid power train would improve the 0-60 mph acceleration by about 1 second and reduce fuel consumption by about 20%, but such a transmission is not likely to be available before 1985.

*The power train for this vehicle is not fully optimized because it must utilize automotive components available in 1982. Thus its fuel economy and resultant petroleum savings are less than those of the more highly optimized hybrid vehicles discussed in Appendix B (Volume I, Section 8).

(7) The operation of the heater/defroster and air-conditioner significantly increases the energy-use of the hybrid vehicle when the electric motor is the primary propulsion unit.

2.5 TASK 4 - SENSITIVITY ANALYSIS

This subsection summarizes the work done on Task 4 which is fully reported in Appendix D - Sensitivity Analysis Report.

2.5.1 OBJECTIVES

The major objectives of the Task 4 study were to determine the impact of variations (from nominal values) in

- Travel characteristics
- Energy costs
- Component costs
- Vehicle lifetime
- Maintenance costs
- Fuel economy of the Reference ICE vehicle

on the

- Utility
- Economic attractiveness
- Marketability

of the 5-passenger hybrid vehicle selected as near-optimum in Task 2.

2.5.2 METHODOLOGY

The sensitivity studies were performed using the Hybrid Vehicle Design (HYVELD) computer program which was also employed extensively in the Design Trade-off Studies. HYVELD was developed so that the important parameters on which the vehicle design and economics depend could be easily changed by simply altering the inputs to the program.

A summary of the parameter sensitivities studied using HYVELD is given in Table 2.5.2-1. About 50 runs were made - divided into the groups indicated - to investigate the effect of one or, at most, three parameters at a time. All the studies pertain to the parallel hybrid configuration (without secondary energy storage) and are for a power-to-weight ratio Kp equal to 0.02 kW/lb. The sensitivity of hybrid vehicle design to power train configuration and component characteristics was studied in detail in Task 2 and was not repeated in Task 4. The HYVELD calculations yielded parametric results for other hybrid/electric vehicle configurations, but those results are not discussed in this task because the Design Trade-Off Studies indicated clearly that the parallel hybrid approach was far superior to the others.

Thus, it is the sensitivity of the parallel hybrid results to the parametric variations that is of prime importance.

2.5.3 CONCLUSIONS

The major conclusions drawn from the sensitivity analysis are the following:

(1) Changes in annual mileage are reflected directly in the fraction of the miles that the hybrid vehicle can be driven primarily on electricity with the marginal effect increasing rapidly when the fraction falls below 50%.

(2) For the lowest cost dc electric drive system and high-volume production, the initial cost of the hybrid vehicle would be $1200 to $1500 higher than that of the conventional ICE vehicle. This cost differential would be $1600 to $2100 for low-volume production of the electric components.

(3) For nominal energy costs ($1.00/gal for gasoline and 4.2¢/kWh for electricity), the ownership cost of the hybrid vehicle is projected to be 0.5 to 1.0¢/mi less than the conventional ICE vehicle. To attain this ownership cost differential, the lifetime of the hybrid vehicle must be extended to 12 years and its maintenance cost reduced by 25% compared with the conventional vehicle.

(4) The ownership cost advantage of the hybrid vehicle increases rapidly as the price of fuel increases from $1 to $2/gal. The effect of the cost of electricity on ownership cost is small for electricity prices between 2.5¢ and 8.5¢/kWh.

(5) Annual mileage and fraction of miles in urban driving do not significantly affect the ownership cost differential between the hybrid and conventional vehicles.

(6) Changes in general economic conditions (i.e., the inflation rate) do not significantly affect the ownership cost differential between the hybrid and conventional vehicles.

(7) Annual fuel savings using the hybrid vehicle are strongly dependent on the fuel economy baseline used for the Reference ICE Vehicle (1985 model). Using projected 1985 fuel economy values, the hybrid vehicle would have a fuel savings of about 55% or 250 gal per vehicle per year.

(8) Hybrid vehicles would be economically attractive to a wide group of new car buyers with the ownership cost and fraction of fuel saved varying only slightly between the 35th and 90th percentile of car owners.

Table 2.5.2-1

SUMMARY OF PARAMETER SENSITIVITIES
STUDIED USING HYVELD

Sensitivity to	Parameters Varied	Number of Combinations
Energy Costs	Gasoline Price, Electricity Price	8
Annual Mileage	Annual Mileage	4
Fraction of mileage in City	Fraction of Mileage in City	4
Economic Conditions	Discount Rate, Interest Rate, Inflation Rate	3
Vehicle Lifetime and Maintenance Improvement	Vehicle Lifetime, Additional Cost Factor to Extend Life, Maintenance Improvement Factor	8
Percentile of Vehicle Random Travel	Annual Mileage, Fraction of Mileage in City, Vehicle Electric Range	12
Engine Type	Engine Type (Diesel and Gasoline), Diesel Fuel Price	4
Reference ICE Vehicle Fuel Economy	Urban and Highway Fuel Economy of the ICE Vehicle	3
Electric Drive-line Component Costs	Specific Cost of Each Electric Drive-line Component for Low and High Production Rates	6

(9) The economic attractiveness of the hybrid vehicle is not a strong function of design electric range for changes in range between 30 to 40 mi.

(10) Hybrid vehicles using diesel engines have a slight advantage in ownership cost (0.5 - 1.0¢/mi) compared to those using gasoline engines, but the gasoline engine-powered hybrid has a slightly greater ownership cost differential advantage compared to the corresponding conventional ICE vehicle (1985 model).

Section 3

SUMMARY OF THE NEAR-TERM HYBRID VEHICLE DESIGN

A summary of the Near-Term Hybrid Vehicle preliminary design is presented in this subsection. Topics addressed include the general layout and styling, the power train specifications with discussion of each major component, vehicle weight and weight breakdown, vehicle performance, measures of energy consumption, and initial cost and ownership cost.

3.1 GENERAL LAYOUT AND STYLING

The general characteristics of the vehicle layout and chassis are:

- Curb weight
  - 1786 kg (3930 lb)
- Body Style
  - Four-door hatchback
  - Drag Coefficient - 0.40 (effective wind weighted)
  - Frontal area - 2.0 m^2 (21.5 ft^2)
- Rolling Resistance
  - .011 lb/lb (tires plus wheel bearings)
- Chassis/Power Train Arrangement
  - Front wheel drive
  - Complete power train, including the batteries, in front of firewall
  - Fuel tank under rear seat
- Reference ICE Vehicle
  - Chevrolet Malibu (1985 model)*

Full-scale drawings of the near-term hybrid vehicle have been prepared and 1/5 scale reductions are included in Appendix C, Preliminary Design Data Package. The starting point in preparing

*The Reference ICE Vehicle (1985 model) is assumed to have the same frontal area, drag coefficient, and rolling resistance as the hybrid/electric vehicle.

the drawings was the 1979 Malibu. No changes were made in the seating package. A three-dimensional cutaway of the hybrid vehicle indicating the placement of the power train is shown in Figure 3.1-1. Note that the complete hybrid power train is located in front of the firewall with no intrusion into the passenger compartment. An artist's rendering of the vehicle styling is shown in Figure 3.1-2. A four-door hatchback body type was selected because it maximizes the all-purpose character of the five-passenger vehicle.

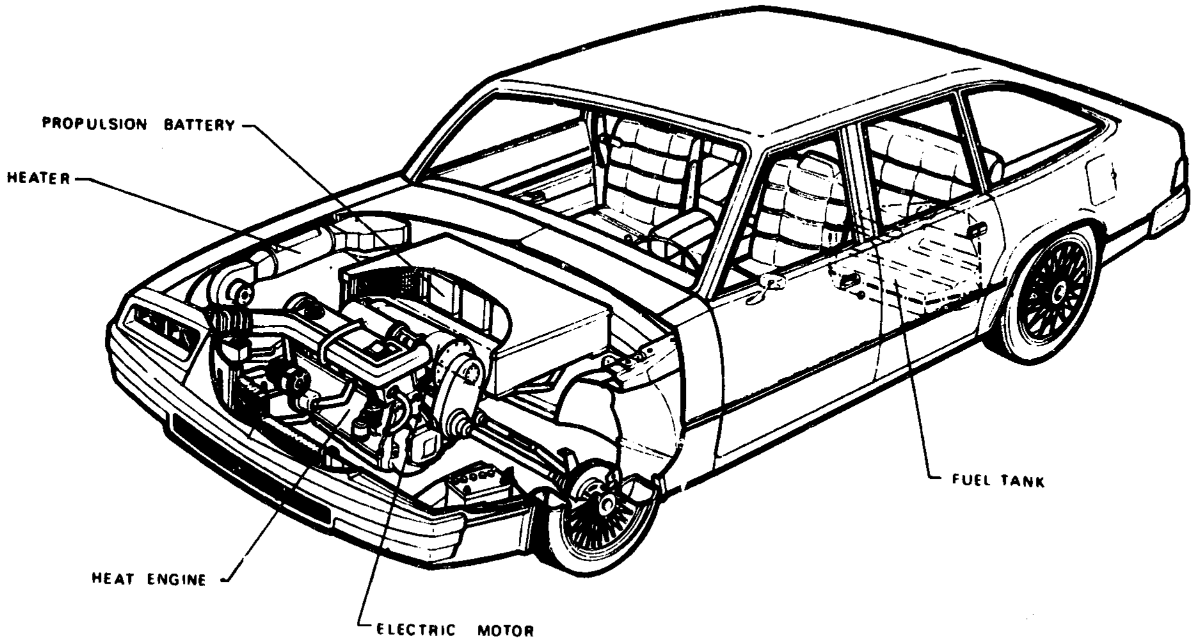
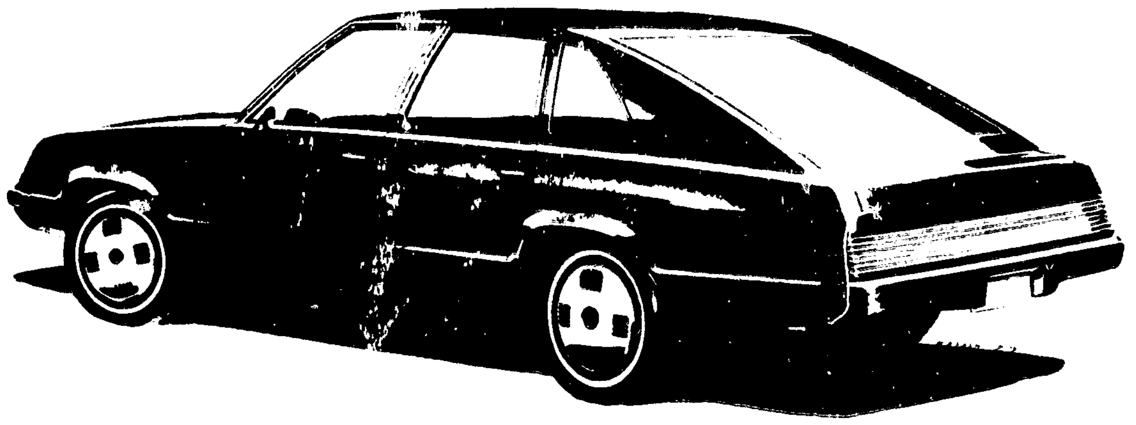
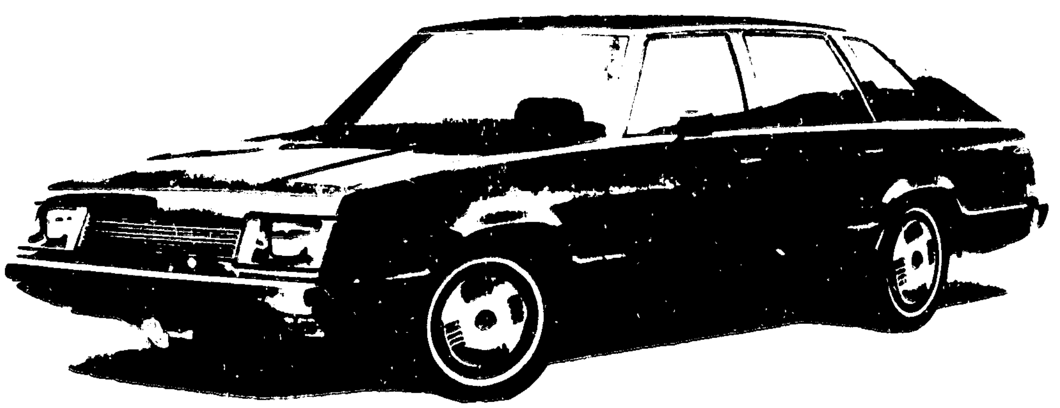


Figure 3.1-1. Near-Term Hybrid Vehicle, Three-Dimensional Cutaway



Left Rear Quarter View



Left Front Quarter View

Figure 3.1-2. Artist's Rendering of the Near-Term Hybrid Vehicle

3.2 POWER TRAIN SPECIFICATIONS AND WEIGHT BREAKDOWN

Specifications for the heat engine, electric drive system, batteries, and transmission and axle differential are presented in this subsection. Control strategy and the system microcomputer are discussed and the vehicle weight breakdown is presented.

3.2.1 POWER TRAIN SPECIFICATIONS

Full-scale drawings of the hybrid power train were prepared in Task 3. A one-fifth scale drawing of the power train is shown in Figure 3.2.1-1. As indicated in the figure, the hybrid vehicle uses front-wheel drive with both the heat engine and electric motor mounted in a transverse orientation above the transaxle. This is clearly a parallel hybrid configuration. Clutches are required to permit decoupling the drive system from the vehicle drive shaft and operating the heat engine and electric motor in combination and separately. A schematic of the power train is shown in Figure 3.2.1-2.

Specifications for each of the power train components are discussed in the following subsections.

3.2.1.1 Heat Engine

The heat engine used in the preliminary design of the hybrid vehicle is the Volkswagen fuel-injected 4-cylinder, 1.6 liter gasoline engine. This engine equipped with the Bosch K-Jetronic fuel injection system is used in the VW Rabbit and Audi 4000. The K-Jetronic system is often referred to as the CIS (Continuous Injection System) and utilizes a mechanical airflow sensor and distributing slots to control fuel flow to the engine. The VW 1.6 liter engine can also be equipped with the Bosch L-Jetronic system which utilizes solenoid-operated injection valves associated with each cylinder. The amount and timing of the fuel injection is controlled by a microprocessor which requires inputs from measurements of airflow, rpm, engine temperature, etc. The L-Jetronic system is a true electronically controlled fuel injection system and for that reason is more compatible with the overall implementation of the hybrid vehicle control strategy using a system microprocessor. Volkswagen does not currently market the L-Jetronic fuel injection system. However, discussions with VW indicated they are currently fleet-testing cars using the L-Jetronic system and have done much laboratory testing of engines using that system. Hence it is appropriate to use the more advanced L-Jetronic system in the Near-Term Hybrid Vehicle Program.

Considerable fuel consumption and emission data were available to characterize the electronically fuel-injected (EFI), 1.6-liter engine. Those data were used in the HYVEC simulation

studies. The EFI 1.6-liter engine is rated at 80 hp at 5500 rpm with a maximum torque of 84 ft/lb at 3200 rpm. Hence, the engine is sized almost exactly to meet the hybrid vehicle power requirement and is an ideal choice for the hybrid application.

3.2.1.2 ELECTRIC DRIVE SYSTEM

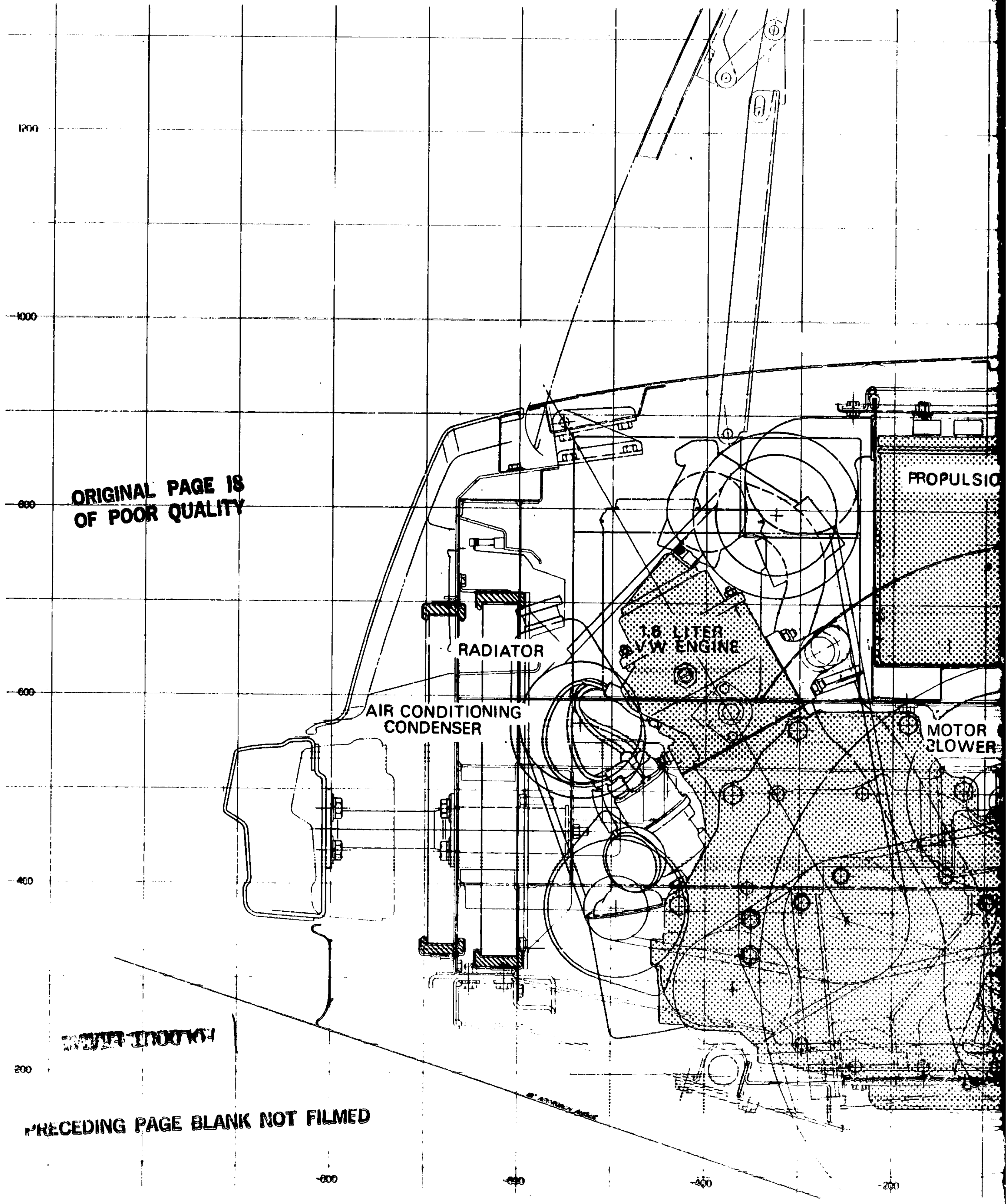
The electric drive system in the hybrid vehicle utilizes a dc separately excited motor with battery switching and field weakening to control motor speed and torque. The system uses a nominal voltage of 120 V with peak currents of about 400 A except during battery switching when the currents reach 500 A for a few seconds. The electric motor has a continuous rating (1-2 hours) of 18 kW (24 hp) and a peak rating (1-2 minutes) of 32.8 kW (44 hp). Discussions with the General Electric DC Motor and Generator Department indicate that the dc motor for the hybrid vehicle can be developed by a modest redesign of the electric motor used in the Near-Term DOE/GE electric car. The resultant motor for the hybrid vehicle would be essentially the same size (length and diameter) and weight as the one for the DOE/GE electric car, but it would be worked harder (with slightly higher currents and flux) in the hybrid application. Testing of the original design has indicated this is possible without significantly reducing the reliability and life of the motor.

The dc motor is controlled using field weakening and battery switching. The battery is arranged in two parallel banks so that it can be operated to yield 60 V or operated in series to yield 120 V. The base speed of the motor is 1100 rpm at 60 V and 2200 rpm at 120 V. A resistor is used when starting the motor and during short periods of battery switching. Field weakening is accomplished using a transistorized field chopper in essentially the same way as in the DOE/GE electric car.

The motor rating may be summarized as follows:

<u>Design No. 2366-2913</u>

Frame	OD 12 1/4 in.
Name Plate Rating	24 HP, Peak Power 44 hp (1 min.)
Weight	220 lb
Rated Voltage	108 V
Rated Current	190 A
Rated Field	8.2 A
Rated Flux	0.84 Megalines
Base Speed	2200 rpm
Maximum Speed	6000 rpm


1200
1000
800
600
400
200
RADIATOR
AIR CONDITIONING
CONDENSER
1.6 LITER
V.W ENGINE
MOTOR
-800
-600
-400
-200

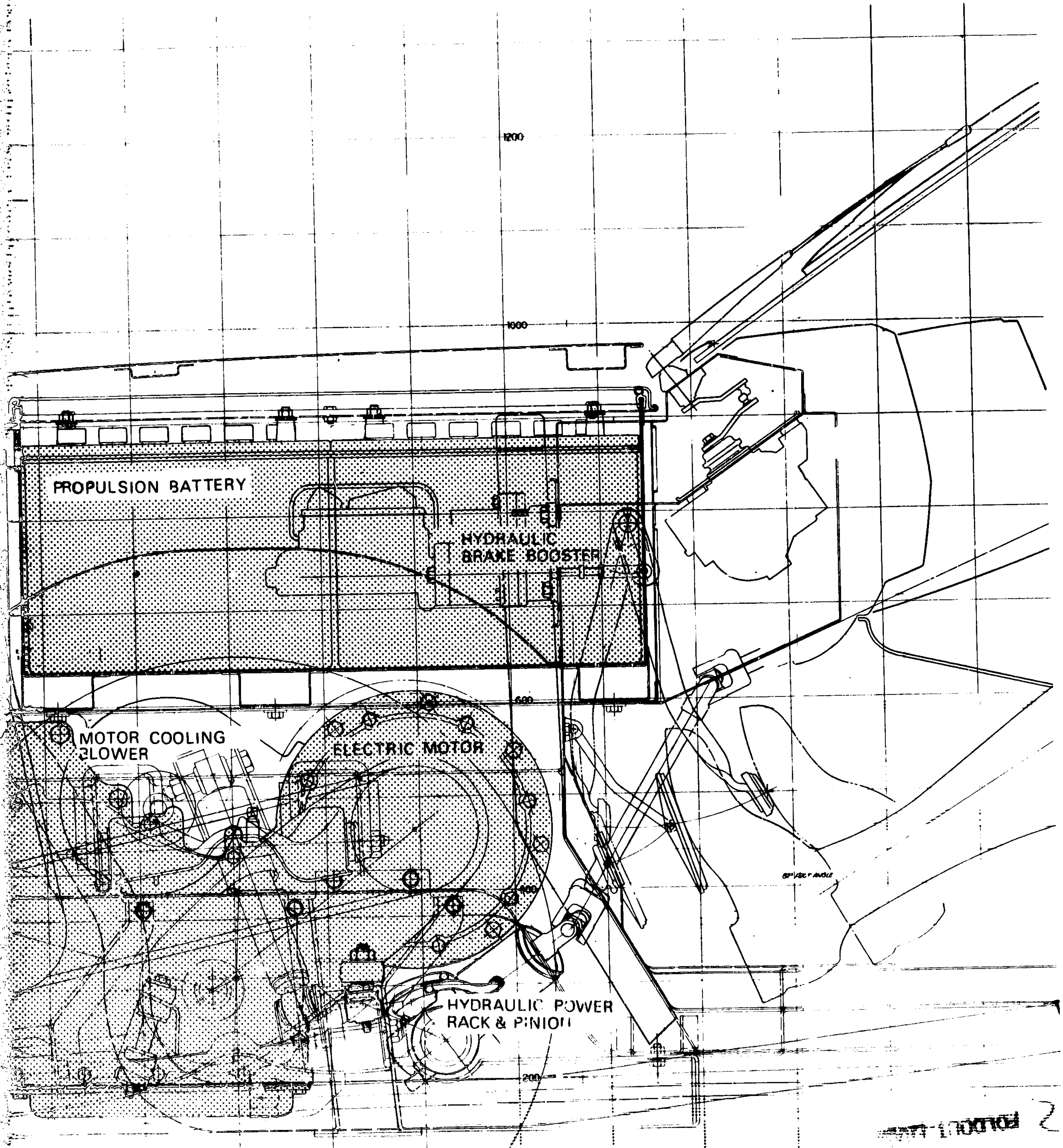


Figure 3.2.1-1. Hybrid Power Train

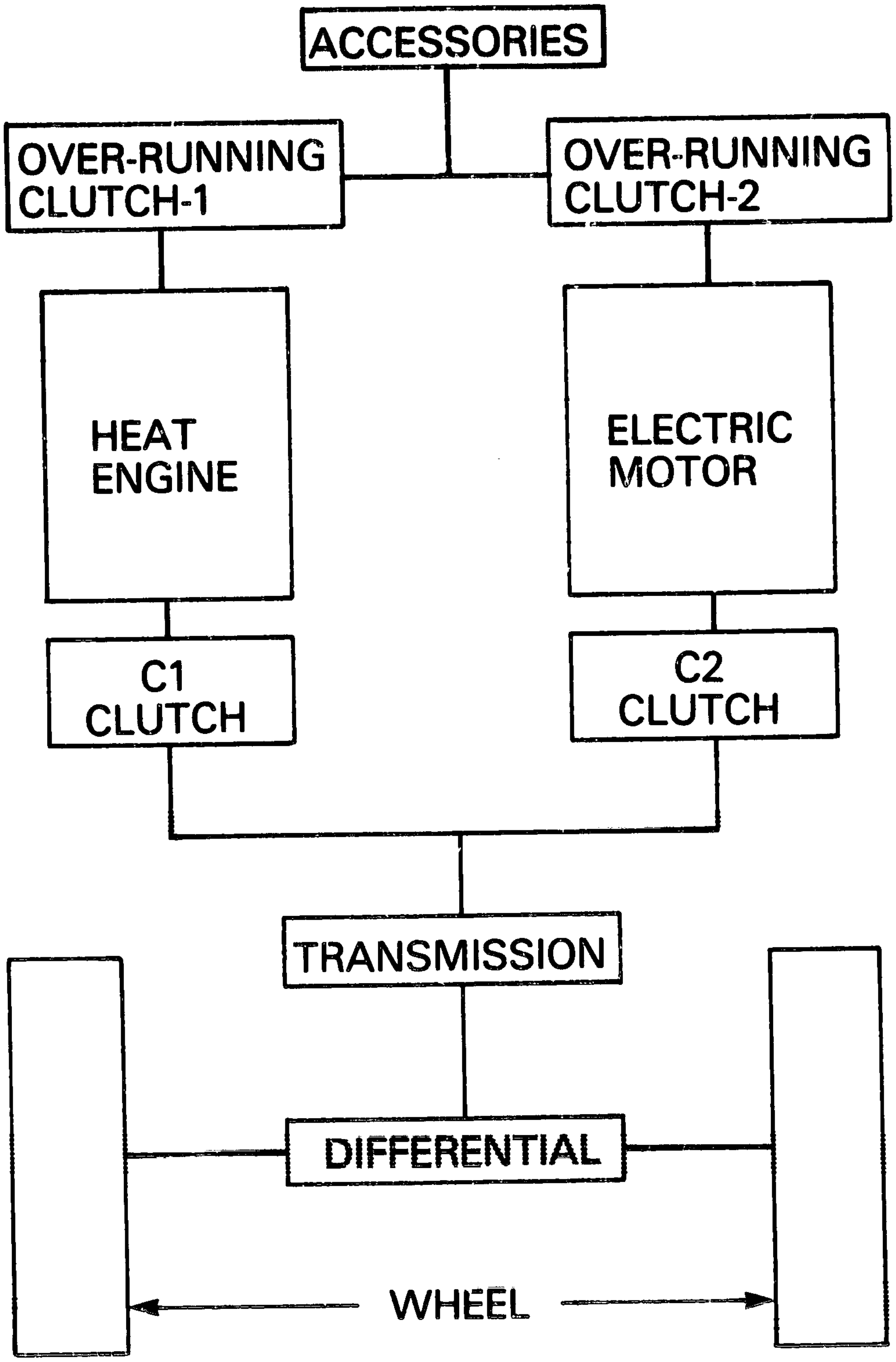


Figure 3.2.1-2. Schematic of Drive Package

3.2.1.3 Batteries

The hybrid vehicle is designed to utilize 770 lb of Improved State-of-the-Art (ISOA) lead-acid batteries. The batteries are positioned under the hood in front of the firewall as shown in Figure 3.2.1-1. The battery container has dimensions of 36 in. length, 26 in. width, and 13 in. height. The preferred battery module is 12 V, 105 AH/cell at the C/3 rate. The 770-lb battery pack stores 12.5 kWh at the C/3 rate for an energy density of 16.4 Wh/lb. The power characteristics of the battery are based on the voltage-current relationship for a 15 second pulse at 50% state-of-discharge during a C/3 rate discharge. The power characteristics specifications are the following:

Pulse Current, A	Volts/Cell	Volts/Module
210	1.82	10.9
315	1.71	10.3
420	1.61	9.6

For the maximum current pulse of 420 A, the corresponding power density is about 53 W/lb with a voltage droop of 20%. The lead-acid batteries used in the preliminary design of the hybrid vehicle have energy density and power characteristics comparable to those of the batteries developed by Globe-Union for the DOE/GE electric car. The cell capacity (AH) for the hybrid vehicle battery is considerably smaller, however, which means that new batteries must be designed and fabricated especially for the hybrid application.

3.2.1.4 Transmission and Axle Differential

For front-wheel drive vehicles, the transmission and axle differential are usually combined in a single unit termed the transaxle. Nevertheless, the speed change characteristics of the transmission and axle differential can be described separately. The transmission is an automatically shifted gearbox taken from an automatic transmission. In the Design Trade-off Studies, a four-speed transmission having an overall gear ratio of 3.46 was used. Such a gearbox would be part of a four-speed, overdrive automatic transmission. Unfortunately, such a transmission in a transaxle unit is not currently being marketed by a U.S. or foreign auto manufacturer or supplier. Such a unit might become available as auto manufacturers seek to improve fuel economy. The gearbox used in the preliminary design studies of the Near-Term Hybrid Vehicle is part of the three-speed automatic transmission used in the new GM X-body cars (e.g., Chevrolet Citation). That gearbox has ratios of 2.84/1.6/1 in 1st, 2nd, 3rd gear respectively. An axle ratio of 3.3 has been used in most of the HYVEC calculations. That value is compatible with maximum motor and engine speeds of 6000 rpm and yields good fuel economy in both urban and highway driving.

3.2.1.5 Torque Combination

The outputs of the heat engine and the electric motor are combined using the single-shaft approach in which there are fixed ratios between the rotational speeds of the heat engine, electric motor, and vehicle drive shaft. HYVEC simulation studies have shown that the heat engine and electric motor can be operated near optimum efficiency by varying the power split in the neighborhood of 50%. This can be done using the system microprocessor and avoids the need for a power differential which would vary the shaft speed ratios as a function of the desired power split between the heat engine and motor. The power differential is much more difficult to control than the single-shaft (fixed speed ratio) arrangement for torque combination. A preliminary drawing of the torque transfer unit, including the clutches required, is shown in Figure 3.2.1-3.

3.2.1.6 Control Strategy and the System Microprocessor

A detailed control strategy for operating the heat engine and electric motor has been developed as indicated in Figure 3.2.1-4. The key features of the control strategy are:

- On/off engine operation
- Regenerative braking whenever the battery can accept the charge
- Regenerative braking whenever the battery can accept the charge
- Electric motor idling when vehicle is at rest
- Electric drive system primary (battery state of discharge permitting) when vehicle speed is less than VMODE*
- Equal sharing of load between motor and engine when both are needed.
- Batteries recharged by heat engine in a narrow state-of-charge range ($0.7<S<0.8$)
- Electric motor dominant in determining shifting logic when it is operating
- Heat engine primary for highway driving
- Electric motor always used to initiate vehicle motion from rest and in low-speed maneuvers (e.g., parking)
- Vehicle operation controlled by a system microprocessor.
- Accessories driven by heat engine or electric motor, whichever is primary, and accessory load shared when both are operating.

Considerable work has been done to develop the microprocessor control logic (software) corresponding to the control strategy

*Vehicle speed at which the heat engine becomes the primary source of power

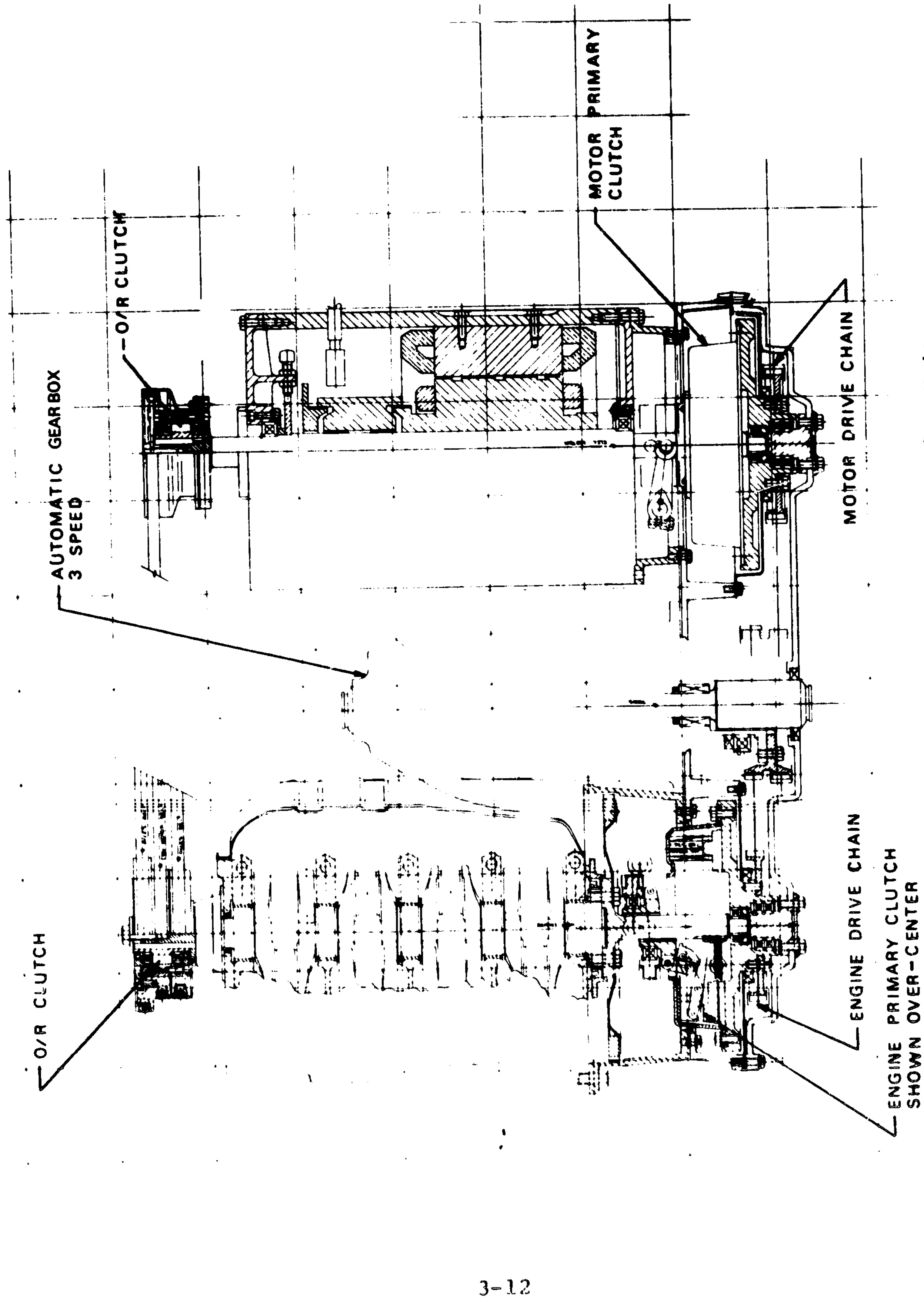


Figure 3.2.1-3. Torque Transfer Unit

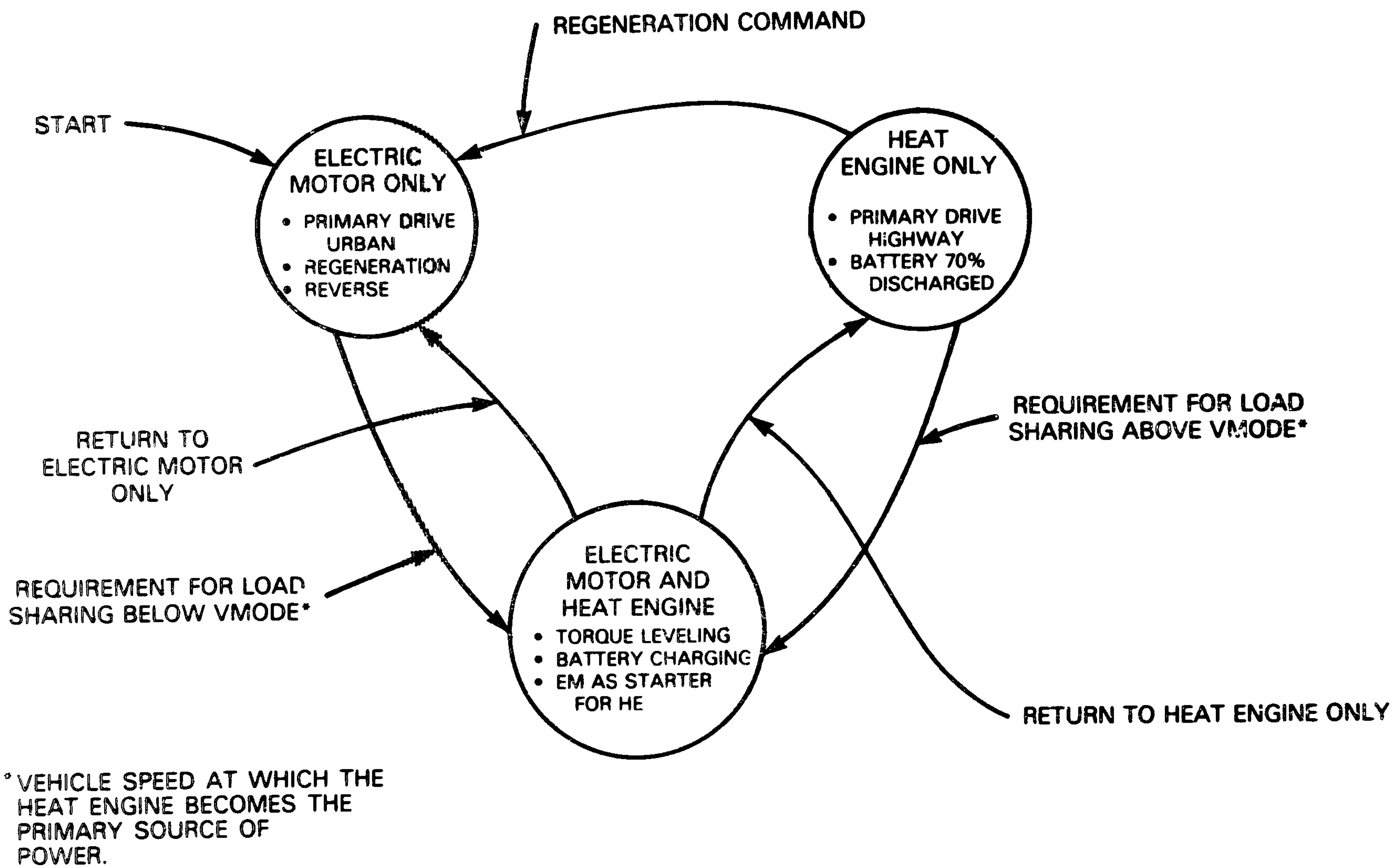


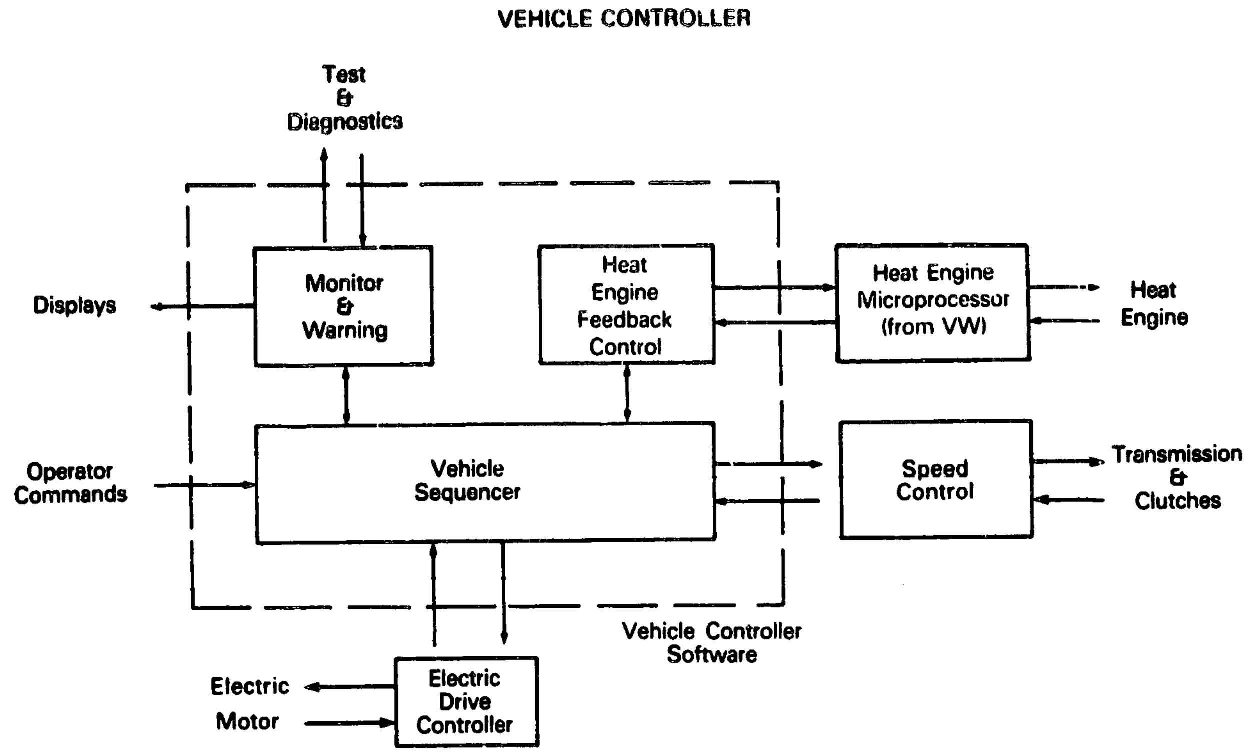
Figure 3.2.1-4. Propulsion Source Sequencing Strategy

used in the HYVEC simulations. The general approach taken is to develop a system controller which receives inputs from the microprocessors governing the heat engine and electric motor and which in turn sends control signals to those prime movers. The various microcomputer functions are shown in Figure 3.2.1.5.

3.2.2 VEHICLE WEIGHT AND WEIGHT BREAKDOWN

A weight breakdown for the Near-Term Hybrid Vehicle is given in Table 3.2.2-1. A vehicle curb weight of 3928 lb is projected leading to an inertia test weight of 4228. This is 228 lb greater than the 4000 lb used in the HYVEC calculations given in the Design Trade-Off Study Report.* The hybrid vehicle simulations have been rerun using HYVEC to include the effects of the increased vehicle weight and other changes in power train component characteristics made during the Preliminary Design Task. The HYVEC results for the Near-Term Hybrid Vehicle design are used in the discussions of vehicle characteristics presented in subsequent sections.

*The weight used in the Design Trade-Off Studies assumed optimum use of 1985 automotive technology and materials and a complete ground-up design. All the automotive components needed to do this will not be available by 1981/82 for use in the Near-Term Hybrid Vehicle. Hence its weight is greater than that of the optimum design.



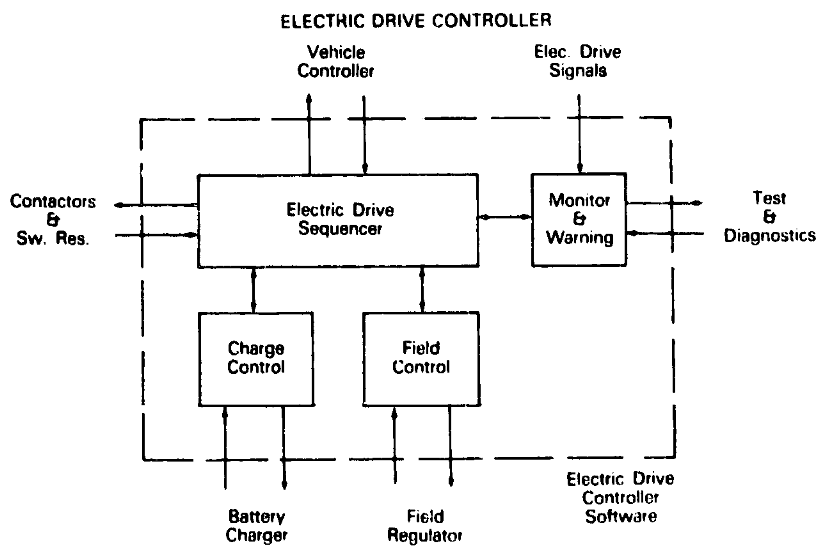


Figure 3.2.1-5. Hybrid Vehicle Microcomputer Control

Table 3.2.2-1

WEIGHT BREAKDOWN - MALIBU BASED HYBRID

	Weight (lb)	
Chassis/Running gear		
Structure	806	
Bumpers	164	
Suspension	230	
Wheels and tires	254	
Brakes	128	
Subtotal		1582
Exterior/Interior/Control		
Seats	104	
Skins	153	
Human factor and control	484	
Air-conditioner	113	
Subtotal		854
Power train		
Gasoline engine (VW 1.6ℓ)	284	
Fuel system (incl. 10 gal. gasoline)	78	
Transaxle	90	
Electric motor	220	
Power electronics and controller	50	
Lead-acid batteries	770	
Subtotal		1492
Total curb weight		3928 lb (1785 kg)

3.3 VEHICLE PERFORMANCE

A format for presenting and discussing the performance specifications of the hybrid vehicle and how well the preliminary design meets or exceeds the minimum specifications was set forth by JPL in the RFP for the contract. That format was followed in this and subsequent sections of this report, but for convenience of discussion the complete list (P1 to P17) will be divided into several parts. In this subsection, items P1 to P9 are considered. These items deal directly with vehicle performance, operation, and cost under normal (or routine) operating conditions and have been studied in considerable detail in the Phase I effort. Some of the other items which refer more to nonroutine vehicle operation, such as cold weather conditions, have not been studied in as great detail.

Vehicle performance characteristics of the preliminary design are given in Table 3.3-1 for items P1 through P9. In all respects, the Near-Term Hybrid Vehicle design meets or exceeds the minimum requirements. This includes minimum requirements R1 through R6 and constraints C1 through C6. The values given in Table 3.3-1 were taken from the updated HYVEC Calculations.

Initial estimates of battery rechargeability and maintenance (P11, P12) and cold/hot temperature operation (P10, P13) are given in Table 3.3-2. Considerable work is needed in Phase II to refine the estimates given in the table, especially in the area of battery warm-up after long soak periods at subzero temperatures.

Table 3.3-1

VEHICLE PERFORMANCE CHARACTERISTICS

P1	Minimum Nonrefueled Range				
P1.1	FHDC (Gasoline - 10 gal. tank)			550 km[a]	
P1.2	FUDC			120 km,[b]	400 km[a]
P1.3	J227a(B) (all-electric operation)			80 km[a]	
P2	Cruise Speed			130 km/h	
P3	Maximum Speed				
P3.1	Maximum Speed			150 km/h	
P3.2	Length of Time Maximum Speed Can Be Maintained on Level Road			1 min	
P4	Accelerations				
P4.1	0-50 km/h (0-30 mph)			5.0 s	(6.0)[c]
P4.2	0-90 km/h (0-56 mph)			12.6 s	(15.0)[c]
P4.3	40-90 km/h (25-56 mph)			8.6 s	(12.0)[c]
P5	Gradability	Grade	Speed		Distance
P5.1		3%	100 km/h (90)[c]		(Unlimited)[e]
P5.2		5%	95 km/h		(Unlimited)
P5.3		8%	80 km/h (50)[c]		(Unlimited)
P5.4		15%	40 km/h (26)[c]		(Unlimited)
P5.5	Maximum Grade	25%	——		——
P6	Payload Capacity (including passengers)				535 kg
P7	Cargo Capacity				0.5 m^3
P8	Consumer Costs				
P8.1	Consumer Purchase Price (1978 $)				$7600
P8.2	Consumer Life Cycle Cost (1978 $)				0.11 $/km
P9	Emissions - Federal Test Procedure[d] (Gasoline Engine)				
P9.1	Hydrocarbons (HC)				0.09 gm/km, 0.13 gm/km
P9.2	Carbon Monoxide (CO)				0.62 gm/km, 0.79 gm/km
P9.3	Nitrogen Oxides (NO_x)				0.48 gm/km, 0.57 gm/km

(a) Range at which the 10 gallon tank is empty.

(b) Range at which the battery is first recharged by the heat engine.

(c) JPL minimum specifications.

(d) The first number corresponds to first 50 km, second to 120 km.

(e) On heat engine alone.

Table 3.3-2

VEHICLE PERFORMANCE CHARACTERISTICS

P10	**Ambient Temperature Capability**	
	Temperature range over which minimum performance requirements can be met.	-20 °C to 40 °C
P11	**Rechargeability**	
	Maximum time to recharge from 80% depth-of-discharge (routine charge to 96% capacity)	6 hr
P12	**Required Maintenance (Battery)**	
	Routine maintenance required per month	
	Watering (1 or less, depending on use)	15 min/ea.
	Equalization charge (2-4, depending on use)	12-15 hr/ea.
P13	**Unserviced Storability**	
	Unserviced storage over ambient temperature range of -30 °C to +50 °C	
	P13.1 Duration	$\geq$ 5 days
	P13.2 Warm-up time required	
	Battery heating (-20 °F)	10-15 min
	Engine starting	<30 s

3.4 MEASURES OF ENERGY CONSUMPTION

The energy use of the Near-Term Hybrid Vehicle on the various driving cycles has been calculated using the HYVEC simulation program. The updated results are given in Figures 3.4-1 and 3.4-2.

A format for summarizing the measures of energy consumption of the hybrid vehicle was given by JPL in the RFP for the contract. Values for these energy-use measures (E1 through E8) are given in Table 3.4-1. No values are given for life cycle energy consumption per vehicle compared to the Reference ICE Vehicle, because information was not available concerning the energy required to fabricate and to dispose of the hybrid vehicle. Since the hybrid vehicle is about 1000 lb heavier than the Reference ICE Vehicle, it is reasonable to assume that the energy needed to fabricate the hybrid vehicle would be higher, but the net difference in fabrication energy will depend on the recycle pattern of those components which cause the weight difference between the vehicles. For example, much of the lead in the batteries and copper in the electric motor would be recycled with a significant favorable effect on the life cycle energy consumption of the hybrid vehicle. The material used to fabricate the exterior shell (doors, fenders, hood, etc.) of the vehicle will also have a strong influence on life cycle energy use. Life cycle energy use, including fabrication and disposal, will be considered during material selection in Phase II, but to date that subject has received only minimal attention.

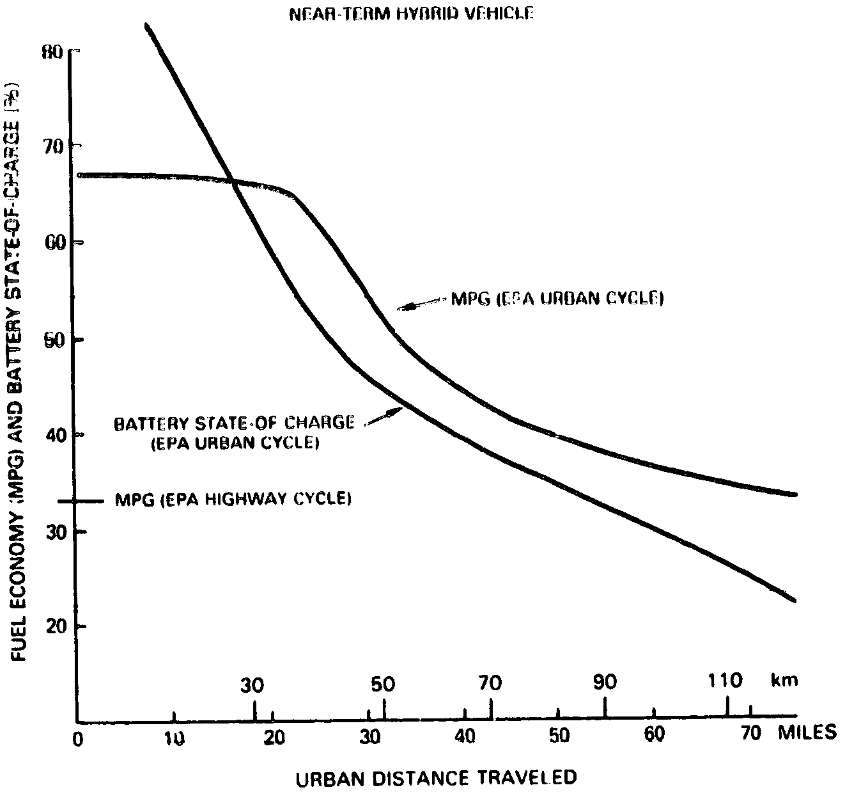


Figure 3.4-1. Battery State-of-Charge and Fuel Economy for Urban and Highway Driving

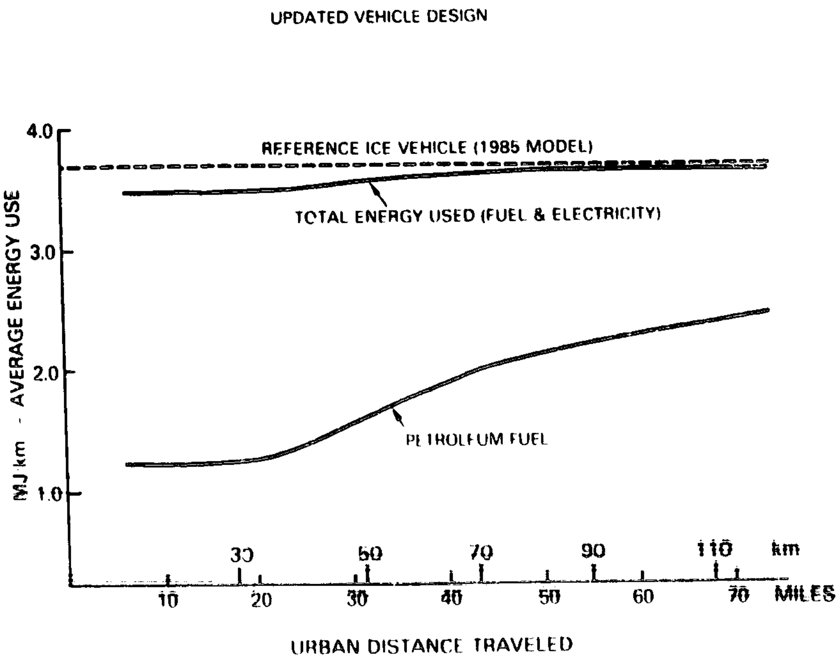


Figure 3.4.2. Total Energy and Petroleum Fuel Usage in Urban Driving

Table 3.4-1

ENERGY CONSUMPTION MEASURES (Near-Term Hybrid Vehicle)

E1	Annual petroleum fuel energy consumption per vehicle compared to reference vehicle over contractor-developed mission[a]	25,710 MJ SAVED[b]
E2	Annual total energy consumption[c] per vehicle compared to reference vehicle over contractor-developed mission[a]	3,425 MJ SAVED[b]
E3	Potential annual fleet petroleum fuel energy savings compared to reference vehicle over contractor-developed mission[c]	25×10^9 MJ
E4	Potential annual fleet total energy consumption[c] compared to reference vehicle over contractor-developed mission[d]	3.4×10^9 MJ SAVED[b]
E5	Average energy consumption[c] over maximum nonrefueled range	
	E5.1 FHDC (gasoline only)	2.45 MJ/km (32 mpg)
	E5.2 FUDC[e]	3.59 MJ/km, 3.68 MJ/km, 3.8 MJ/km
	E5.3 J227a (B) (electricity only)	2.45 MJ/km
E6	Average petroleum fuel energy consumption over maximum nonrefueled range	
	E6.1 FHDC	2.45 MJ/km (33 mpg)
	E6.2 FUDC[e]	1.5 MJ/km (54 mpg), 2.45 MJ/km (33 mpg), 3.4 MJ/km (23.5 mpg)
	E6.3 J227a (B)	0 MJ
E7	Total energy consumed[c] versus distance traveled starting with full charge and full tank over the following cycles	
	E7.1 FHDC	2.45 MJ/km (Not a Function of Distance)
	E7.2 FUDC	(See Figure 1.4.1-4)
	E7.3 J227a (B)	2.45 MJ/km (Not a Function of Distance)
E8	Petroleum fuel energy consumed versus distance traveled starting with full charge and full tank over the following cycles[f]	
	E8.1 FHDC	2.45 MJ/km (Not a Function of Distance)
	E8.2 FUDC	(See Figure 1.4.1-4)
	E8.3 J227a (B)	0 MJ/km (Not a Function of Distance)

1 MJ = 0.278 kWh = 948 Btu = .00758 gal gasoline

10^9 MJ/yr = 452 barrels crude oil/day

(a) Mission is 11,852 mi/yr; 65% EPA urban cycle, 35% EPA highway cycle

(b) The annual fuel and energy usages of the Reference ICE Vehicle (1985 model) are 456 gallons of gasoline and 60,158 MJ. A fleet of one million Reference Vehicles would use 60×10^9 MJ.

(c) Includes energy needed to generate the electricity at the power plant (35% efficiency)

(d) For one million hybrid vehicles replacing one million Reference Vehicles

(e) The first number corresponds to the first 50 km; the second number to 120 km; the third number to 425 km, at which the gasoline tank is empty

(f) Does not include petroleum consumption resulting from generation of wall plug electricity used by the vehicle

3.5 INITIAL COST AND OWNERSHIP COST

The initial and ownership costs of the hybrid vehicle have been calculated using the methodology discussed in Section 6. An initial cost breakdown is shown in Table 3.5-1. The hybrid vehicle selling price is estimated to be $7667 compared with $5700 for the Reference ICE Vehicle.* The difference in power train costs is $1562. Both the vehicle selling price and the power train cost difference are somewhat higher than found previously in the Design Trade-Off Study. The differences are due primarily to the more detailed information that is now available concerning the size and cost of the power train components.

The ownership cost of the Near-Term Hybrid Vehicle has been calculated from results obtained in the Design Trade-Off Study task by correcting for the change in selling price of the hybrid vehicle. This was done by calculating the fixed capital recovery factor (FCRS) and applying it to the initial price difference. The change in ownership cost was 0.63¢/mi for the nominal set of economic factors. The ownership costs for the near-term hybrid vehicle are shown in Figure 3.5-1 as a function of the price of gasoline. A breakeven price of gasoline of about $1/gal is indicated in the figure. At gas prices in excess of $1/gal, the hybrid vehicle has a lower ownership cost, resulting in the net annual savings shown in Figure 3.5-2. The sensitivity of the ownership costs to changes in the use pattern and the price of electricity are discussed in detail in Appendix D, Sensitivity Analysis.

*The Reference ICE Vehicle selling price ($5700) is for a 1978 Chevrolet Malibu (V-6) with automatic transmission, air-conditioning, power steering, etc. The corresponding 1979 selling price is $5825 (source: Automotive News, 1979 Market Data Book Issue). It was assumed that the selling price of the 1985 model Reference ICE Vehicle would be the same as that in 1978 in 1978 dollars.

Table 3.5-1

COST BREAKDOWN

		OEM Price ($)	Dealer Sticker Price ($)
Chassis/Shell/Passenger Compartment			
Base vehicle minus ICE power train		3482	
Additional weight		130	
Additional cost for extended life		182	
	Subtotal	3794	4932
Hybrid Power Train*			
Heat engine		463	
Transmission		227	
Electric motor		365	
Controller (including microprocessor, field chopper, battery switching)		244	
Batteries (lead-acid)		688	
Battery charger (on-board)		117	
	Subtotal	2104	2735
Total Hybrid Vehicle Price (1978 Dollars)		5898	7667**

*Cost of ICE power train (110 hp) is $1173 (dealer sticker price).
**Cost of Reference ICE Vehicle is $5700 (dealer sticker price - 1978 dollars).

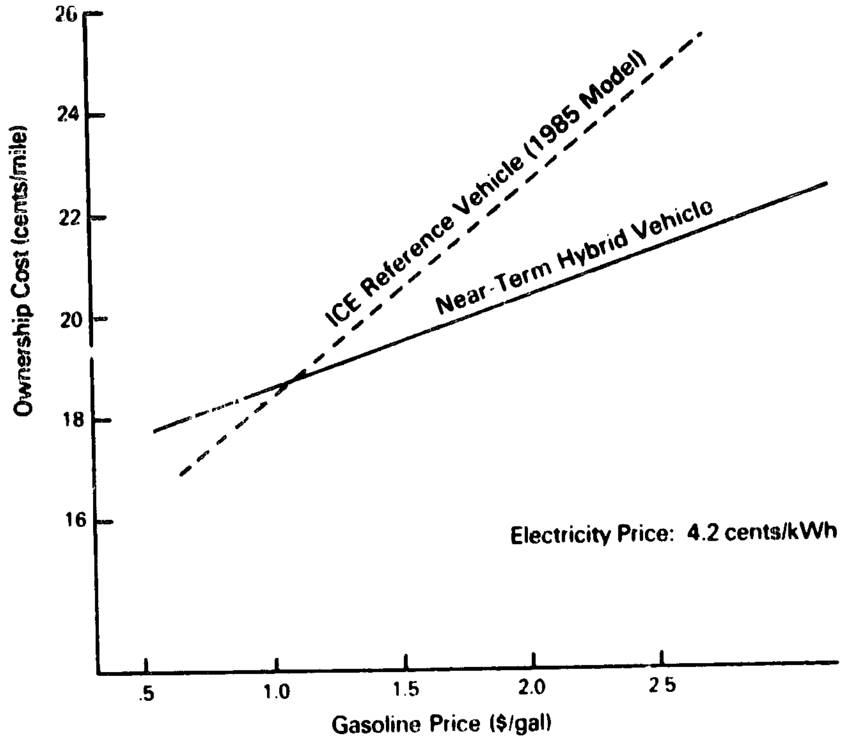


Figure 3.5-1. Ownership Cost as a Function of Gasoline Price

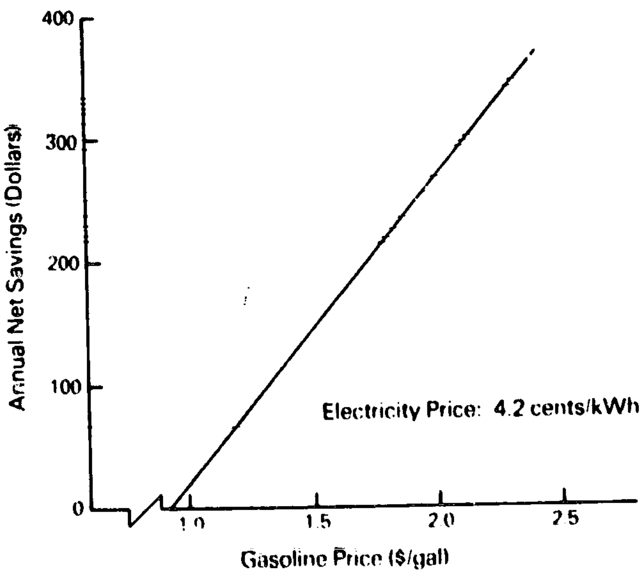


Figure 3.5-2. Annual Net Dollar Savings as a Function of Gasoline Price

Section 4

ALTERNATIVE DESIGN OPTIONS CONSIDERED AND THEIR RELATIONSHIP TO THE DESIGN ADOPTED

Section 4

ALTERNATIVE DESIGN OPTIONS CONSIDERED AND THEIR RELATIONSHIP TO THE DESIGN ADOPTED

4.1 INTRODUCTION

A summary of the alternative design options considered and their relationship to the design adopted is presented in this section. Included are a listing of the factors to be considered as well as a method of ranking, a discussion of parallel vs. series arrangement, a consideration of secondary storage, power split fraction between heat engine and electric motor, battery type, engine type, electric drive options, transmission type and gear ratios, and torque combination options.

Hybrid power train trade-offs were considered in detail in Task 2 of the Phase I study and the quantitative results are discussed completely in Appendix B, Design Trade-Off Studies Report. In this section, those alternative power train options are identified and compared qualitatively with the hybrid power train designed in detail in Task 3.

The power train evaluations done in Task 2 were based on vehicle synthesis calculations and second-by-second computer simulations of hybrid vehicle operation over urban and highway driving cycles. Nearly all the alternative power train options were included in the vehicle synthesis evaluations, but only the most promising of the options were treated in the more detailed simulation studies. The options which were considered in the second step are clearly identified in subsequent discussions. All the calculations were done for five-passenger vehicles which would meet the minimum electric range and acceleration performance specifications set in Task 1 based on the characteristics and the use-pattern of the Reference ICE Vehicle (Chevrolet Malibu).

The hybrid power train option which was selected for the preliminary design task was not the one which in the calculations yielded the "best" hybrid vehicle from a purely technical point-of-view (i.e., lowest weight, maximum fuel economy, and minimum total energy-use). Other considerations, such as initial and ownership costs, maintenance and ruggedness, probability of the availability of components by 1982, likelihood of changes in emission standards, etc., were taken into account in addition to the technical attractiveness of the vehicle in selecting the power train for the Near-Term Hybrid Vehicle. All of these considerations are included in the power train comparisons given in the following sections.

In selecting the hybrid power train a number of decisions had to be made. Fortunately, for the most part the decisions were uncoupled and a decision in one area could be made with a

minimum interaction or dependency on a decision in another area. The same basic control strategy was used with all the power train options as it was essentially dictated by the prime program goal of using electricity to power the vehicle as much as possible on an annual average basis. Decisions had to be made in the following areas:

(1) Parallel or series arrangement

(2) Use of secondary storage - yes or no?

(3) Fraction of peak power from the heat engine (i.e., power split fraction)

(4) Battery type, weight, and size

(5) Engine type

(6) Electric drive type

(7) Transmission type and gear ratios

(8) Torque combination unit

Each of the decisions and the basis for them are discussed in the following sections. For each decision the factors considered are identified and each option is rated relative to the component or approach selected for the Near-Term Hybrid Vehicle.

The rating (or ranking) system used is the following:

+2	significantly better
+1	slightly better
0	reference (selected for the NTHV)
-1	slightly worse
-2	significantly worse
-x	much worse -- reason for eliminating from consideration

Those power train options which were included in the detailed second-by-second simulation studies using HYVEC are identified with an asterisk.

4.2 PARALLEL VERSUS SERIES ARRANGEMENT

The first decision was whether the hybrid power train should utilize a parallel or series arrangement for the heat engine and electric motor. The vehicle synthesis calculations indicated that for the power-to-weight ratio required to meet the acceleration performance specifications, the weight and cost for vehicles using the series arrangement were much higher than those of a vehicle using the parallel arrangement. The differences were above 1100 lb and $2800, respectively. If the comparisons had been made for a much lower power-to-weight ratio (e.g., 0.012 kW/lb rather than .02 kW/lb),† the differences would have been much smaller.

The relative ranking of the series and parallel arrangements are shown in Table 4.2-1. As indicated in the table, the series arrangement was eliminated from further consideration, and all further power train trade-offs were made using the parallel power train configuration which is much better suited for the power sharing required in the high-performance hybrid vehicle discussed in this study.

Table 4.2-1

POWER TRAIN ARRANGEMENT CONSIDERATIONS

Decision Factors	Option Selected Parallel*	Series
Vehicle Weight	0	-x
Vehicle Cost	0	-x
System Control Complexity	0	+1
System Efficiency	0	-1
Energy Use	0	-x

*Included in HYVEC studies

†As shown in Figure 2.2.2-1, this power-to-weight ratio is needed for safe passing in two-lane highways (55 mph) and on that basis has been selected as the design value for the Near-Term Hybrid Vehicle.

4.3 SECONDARY ENERGY STORAGE

Consideration was given to the use of secondary energy storage in the hybrid power train. Vehicle synthesis calculations were made using a composite flywheel or high-power density lead-acid batteries as the secondary storage unit to reduce the power requirements on the primary battery. The calculations indicated that for the power-to-weight ratio of interest (Kp = 0.02 kW/lb) there was not a significant reduction in vehicle weight using secondary energy storage for the cases of lead-acid or Ni-Zn batteries. For higher performance vehicles (Kp > 0.03) or batteries with lower power density, such as Li-S, the reduction in vehicle weight using secondary energy storage would be significant.

Secondary storage considerations are summarized in Table 4.3-1. As indicated in the table, it was decided not to include secondary energy storage in the hybrid power train primarily because the slight improvements in vehicle weight and system efficiency were not large enough to compensate for the uncertainties regarding the availability and cost of the composite flywheel and CVT and the added complexity of packaging a flywheel along with the other components required in the hybrid power train.

Table 4.3-1

SECONDARY STORAGE (FLYWHEEL) CONSIDERATIONS

Decision Factors	Without Secondary Storage	With Secondary Storage (flywheel) (a)
Vehicle Weight	0	+1
Vehicle Cost	0	-1
System Control Complexity	0	-1
Storage Unit Availability	0	-x
Transmission Requirements (b) and Availability	0	-x
System Efficiency and Packaging Requirements	0	-2

(a) composite flywheel
(b) continuously variable transmission

*Included in HYVEC studies

4.4 POWER SPLIT FRACTION

One of the key considerations in designing a parallel hybrid vehicle is the power split between the heat engine and electric drive system. The power split can be expressed in terms of the parameter, F_{HE}, which is the fraction of the peak power which can be supplied by the heat engine alone. The fraction which can be supplied by the electric drive is simply $1 - F_{HE}$. The selection of the engine power fraction depends on both the power-to-weight ratio and battery type used in the vehicle.

Vehicle synthesis calculations showed that for lead-acid and Ni-Zn batteries, F_{HE} equal to about 0.6 results in a near-minimum vehicle weight for $Kp = 0.02$. Use of a larger engine would result in a slightly lower vehicle weight and cost, but unless the absolute power rating of the electric drive system is sufficiently large to permit vehicle operation primarily on electricity in most urban driving the gasoline saved using the hybrid vehicle will be unacceptably small. Hence the general approach in selecting F_{HE} for a specified Kp is to fix the absolute power rating of the electric drive system at that required for most urban driving (i.e., enough power so that at least 75% of the vehicle miles can be driven using the electrical drive system alone) and to determine the heat engine size required to satisfy the remaining power requirements (e.g., 0-60 mph acceleration time). Using this approach, the optimum F_{HE} for minimum vehicle weight and cost increases with Kp.

HYVEC calculations for the EPA urban and highway cycles showed that for a fixed vehicle inertia weight and electric drive system power rating, both the urban and highway fuel economy of the hybrid vehicle decreased as Kp was increased (i.e., as the required size of the heat engine increased). Hence as in a conventional ICE vehicle, the fuel economy of the hybrid vehicle decreases as the acceleration performance of the vehicle is improved. Accounting for engine efficiency and vehicle weight and cost effects, the present study indicates that the optimum engine power fraction would be slightly less than 0.6 for a hybrid vehicle having a 0-60 mph acceleration time of 14-15 seconds.

4.5 BATTERY TYPE

Selection of the battery type and size for the hybrid vehicle was based on vehicle synthesis and detailed simulation calculations. Vehicle designs were studied using the following types of batteries:

- ISOA lead-acid
- Advanced lead-acid (not shown in Table 4.5-2)
- Ni-Zn
- Ni-Fe
- Li-S†

The characteristics of the various batteries are discussed in detail in Appendix B, Volume I, Section 3.4. The results of the battery evaluation, which are summarized in Table 4.5-1, are the basis for the rankings of the battery systems given in Table 4.5-2.

The various battery systems are rated relative to the ISOA lead-acid battery in Table 4.5-2. All the advanced batteries have one or more significant advantages relative to the lead-acid battery, but unfortunately each of the advanced battery systems also has one or more serious drawbacks at least in the near term. In the case of Li-S,† technology is not sufficiently advanced to consider its use in a hybrid vehicle in the time period 1982-85. The other advanced batteries, Ni-Zn and Ni-Fe, were evaluated in detail using the HYVEC program. It was found that the performance of hybrid vehicles using Ni-Zn batteries was very attractive, but that the power characteristics of state-of-the-art Ni-Fe batteries were not good enough for use in the hybrid application. Hence it was concluded that the only two real options available for the Near-Term Hybrid Vehicle were lead-acid and Ni-Zn.

As noted in Table 4.5-2, Ni-Zn batteries have both significant advantages and disadvantages. The advantages are high energy density and good power characteristics. The disadvantages are inadequate cycle life and difficulty in determining the state-of-charge. These disadvantages have persisted for a number of years making the availability by 1982 of Ni-Zn batteries having satisfactory life and charging characteristics very uncertain. In addition, most projections of the cost of Ni-Zn batteries indicate values considerably higher than for lead-acid. For these reasons, it was decided to use the ISOA lead-acid batteries in the Near-Term Hybrid Vehicle. The vehicle design can, however, easily accommodate Ni-Zn batteries if sufficient progress is made in their development in the next few years.

Table 4.5-1

STORAGE UNIT CHARACTERISTICS USED IN THE DESIGN TRADE-OFF STUDIES

Storage Unit Battery Type	Primary Storage: Without Load Leveling			Primary Storage: With Load Leveling		Auxiliary Storage		Cost		Cycle Life a)	Lifetime a)	Energy Exponent b)	Battery Salvage Cost Credit
	Wh/lb	W/lb c)	W/lb d)	Wh/lb	W/lb d)	Wh/lb	W/lb	$/kWh	$/lb	Number of Cycles	Years		
Lead-Acid ISOA	18	[illegible]	65	[illegible]	--	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
Lead-Acid ADV	[illegible]	[illegible]	[illegible]		--		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ni-Zn	[illegible]	--	[illegible]	[illegible]	--	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	[illegible]	[illegible]
Ni-Fe	[illegible]	40	40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Li-S ADV	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Flywheel	--	--	--	--	--	-	[illegible]	[illegible]	[illegible]	10^6	10	N.A.	N.A.

a) The lifetime of the storage unit is calculated from input cycle life or input directly as lifetime in years.

b) $\frac{Wh/lb}{(Wh/lb)_0} = \left(\frac{R}{R_c}\right)^a$

a = energy exponent

R_c = all-electric vehicle design range

R = calculated vehicle range

$\left(\frac{Wh}{lb}\right)_0$ = value given in table

c) [illegible] second pulse

d) 15 second pulse

Table 4.5-2

BATTERY TYPE CONSIDERATIONS

Decision Factor	Battery Type			
	ISOA lead-acid*	Ni-Zn*	Ni-Fe*	Li-S†
Energy Density	0	+2	+1	+2
Power Characteristic	0	+1	-x	0
Cycle Life	0	-2	+2	-1
Initial Cost	0	-1	-1	+1
Near-term Availability	0	-2	-1	-x
Maintenance and Charging	0	-1	-2	-1

*Included in HYVEC studies
†Lithium Aluminum Iron-Sulfide (LiAl-FeSx).

4.6 ENGINE TYPE

As indicated in Table 4.6-1, selection of the heat engine for the hybrid vehicle was dependent on a number of factors. Key considerations were engine weight and size as they affect power train packaging and the current state-of-development of the engines as it affects availability. Based on packaging and near-term availability considerations, only the reciprocating gasoline and turbocharged diesel engines could be considered for use in the Near-Term Hybrid Vehicle. A rotary gasoline engine could have been considered if a single rotor engine of about 70 hp had been available in a highly developed state rather than the two rotor engine (100 hp) used by Mazda in the RX-7. The naturally-aspirated (NA) diesel could have been used if 50 hp had been sufficient to meet the peak power requirements of the Near-Term Hybrid Vehicle designed. A 70 hp NA diesel engine would be too large to fit into the space available for the engine in the hybrid power train.

Table 4.6-1

ENGINE TYPE CONSIDERATIONS*

Decision Factors	Reciprocating Gasoline (fuel injected)[a]	Naturally Aspirating Diesel	Turbocharged Diesel[a]	Rotary Gasoline	Stirling	Gas Turbine
Weight[b]	0	-2	-1	+1	-x	+1
Size[b]	0	-x	-1	+1	-x	+1
Cost[b]	0	-2	-1	-1	-2	-2
Control (on/off mode)	0	-1	-1	-1	-1	-2
Fuel Economy[c]	0	+2	+2	0	+2	-1
Emissions[c]						
Gases	0	0	0	-1	+1	-1
Particulates	0	-2	-2	0	0	0
Transmission Requirements	0	0	0	0	0	-x
Near-Term Availability	0	0	-1	-x[d]	-x	-x

(a) Included in HYVEC studies
(b) Engine characteristic
(c) Vehicle characteristic
(d) Single rotor engines with 70-80 hp are not presently available

*The characteristics of various types of heat engines are discussed in detail in Appendix B (Vol. I), Sec. 3.2. Characterization of heat engines in a single table is not possible and the reader should consult Appendix B for the basis of the rankings given in Table 4.6-1.

Hybrid vehicle simulation calculations were made using both reciprocating gasoline and turbocharged diesel engines. The diesel engine yields higher fuel economy in urban driving for all ranges with the advantage of the diesel being 25% for ranges less than 30 mi and increasing to about 35% at 75 mi. In terms of total energy usage (fuel used by the engine plus that required to generate the electricity at the power plant), the advantage of the diesel powered hybrid is significantly reduced because the higher energy content (per gallon) of the diesel fuel is included in that calculation. The total energy advantage of the diesel is about 6% for ranges less than 30 mi and about 10% at 75 mi. The emissions calculations indicated that both the gasoline and diesel engine-powered hybrid vehicles would easily meet the 1982 emission standards of 0.4 g/mi HC and 3.4 g/mi Co for ranges up to at least 75 mi. The untreated NO_x emissions of the diesel-powered hybrid are lower than for the gasoline powered hybrid, but the use of the three-way catalyst would permit the NO_x emissions of the gasoline hybrid to be reduced to a lower level. Meeting an NO_x standard of 1.0 g/mi for ranges up to 75 mi would not present difficulty with either engine. However, meeting a standard of 0.4 g/mi NO_x would be considerably more difficult with the diesel because the three-way catalyst is not applicable.

The major emissions problem with the diesel is particulates or soot. Simulation calculations indicated soot emissions of about 0.15 g/mi for the first 30 mi and about 0.30 g/mi averaged over 75 mi. The proposed EPA particulate emission standards are 0.6 g/mi in 1981 and 0.2 g/mi in 1982. It would be necessary to reduce the particulate emissions of the turbocharged diesel to meet the 1982 standard.

It was decided to use the fuel-injected 1.6 ℓ VW gasoline engine as the primary engine in the Near-Term Hybrid Vehicle because of the particulate emissions of the diesel and the uncertainty as to whether it could meet the emission standards to be set by EPA for 1982 and beyond. In addition, there was uncertainty regarding the cold-start capability of the diesel engine in the on/off operating mode. The fuel economy advantage of the diesel is attractive, however, and both the particulate emission and potential cold-start problems of diesel should be studied further in Phase II. Since both the gasoline and diesel engine use the same block and thus have much the same exterior profile, the turbocharged diesel could replace the gasoline engine in the hybrid power train without difficulty.

4.7 ELECTRIC DRIVE OPTIONS

The major electric drive system options considered were the dc separately excited motor with armature voltage control or battery switching and the ac induction motor with a pulsed-width modulated (PWM) inverter. In both cases, the power conditioning unit would use high-power transistors similar to those used in the armature chopper in the DOE/GE electric car. The decision factors considered and the relative ratings of the various electric drive systems are given in Table 4.7-1.

Table 4.7-1

ELECTRIC DRIVE SYSTEM CONSIDERATIONS

Decision Factors	dc-Battery Switching*	dc-Armature Control*	ac Induction Motor and PWM Inverter
Size/Weight	0	0	+1
Cost	0	-2	-2
Vehicle Control	0	+1	+1
Efficiency	0	0	+1
Ruggedness	0	-1	-1
Near-Term Availability	0	0	-2

*Included in HYVEC studies

The first decision made was to use the dc drive system rather than the ac. This decision was based on the projected higher cost of the ac system compared with the dc system using battery switching and the relative uncertainty regarding the availability by 1982 of a well-developed induction motor/PWM inverter suitable for use in the hybrid vehicle. The decision as to whether to use battery switching and a slipping clutch or an armature chopper to control the dc separately excited motor at low vehicle speeds was based almost completely on the projected higher cost of the power electronics in the armature chopper system. In addition, the ability of the battery switching circuits to withstand without failure higher currents and overloads than the transistorized armature chopper made control of the hybrid power train somewhat simpler. The decision to use battery switching rather than an armature chopper was a difficult one because it was recognized that the armature chopper afforded superior control of the vehicle at low speeds and that the cost and ruggedness characteristics of the power transistors will likely improve in the next few years as they become more highly developed. It was, however, concluded that for the near term, the battery switching approach would lead to a hybrid design which was more competitive in performance and cost with the conventional ICE vehicle.

4.8 TRANSMISSION TYPE AND GEAR RATIOS

The transmission options considered included gearboxes taken from conventional automatic and manual synchromesh transmissions and a steel-belt, traction-drive continuously variable transmission (CVT). The options are rated in Table 4.8-1 relative to the automatically shifted gearbox which was selected for use in the hybrid vehicle.

Table 4.8-1

TRANSMISSION SELECTION CONSIDERATIONS

Decision Factors	Automatic Gearbox (3 speed)*	Synchromesh Gearbox (4-speed)*	Steel-belt CVT*
Weight/size	0	0	-1
Cost	0	0	-1
Component Efficiency	0	+1	-1
Power Train Control	0	-2	+1
Vehicle Fuel Economy	0	+1	+2
Near-term Availability	0	0	-x

*Included in HYVEC studies

As indicated in the table, both the synchromesh gearbox and the CVT would yield better urban and highway fuel economy, based on hybrid vehicle simulation calculations, than the automatically shifted, three-speed gearbox. The four-speed synchromesh gearbox yielded better fuel economy by 5-10% because of its higher gear ratio range and the absence of hydraulic pumping losses. The prime disadvantage of the synchromesh gearbox is the difficulty in providing smooth, automatic shifting and power train control during the inevitable transients resulting from shifting. The automatic, hydraulically shifted gearbox has internal clutches and bands which permit power transfer during the shift and thus significantly reduce the transients resulting from the shift.

The steel-belt CVT yields better fuel economy because it permits both the electric motor and the heat engine to operate near their optimum torque and efficiency conditions for a wider range of vehicle speeds. In addition, the infinitely variable

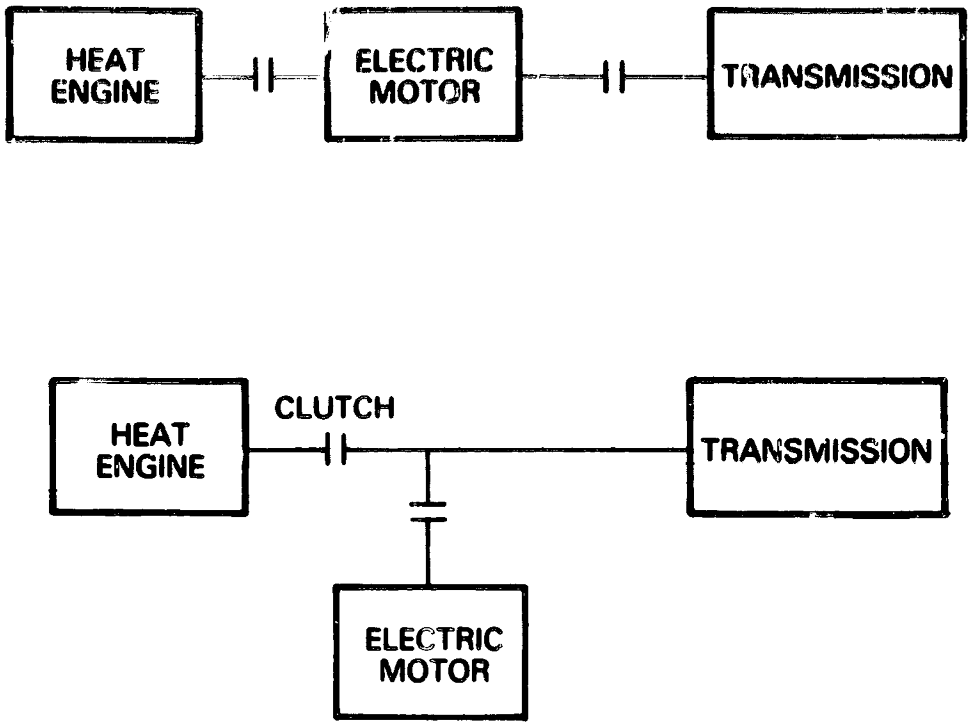
character of the CVT significantly reduces transients during speed changes and thus simplifies the control of the power train. Discussions with the developer of the steel-belt CVT, Borg Warner, indicated that the transmission would not be available before 1985 and that considerable special development would be required for the hybrid application. Hence the CVT was not considered for inclusion in the Near-Term Hybrid Vehicle.

The automatically shifted gearbox used in the hybrid vehicle designed in Task 3 is currently marketed in the GM X-body car. It was designed as a transaxle unit for use with transverse-mounted ICE engines of 125 hp or slightly higher. The GM gearbox is a three-speed unit with an overall gear ratio of 2.85. It would be desirable to utilize a four-speed gearbox having a higher overall ratio if one with the proper shaft configuration should become available in 1980 or 1981.

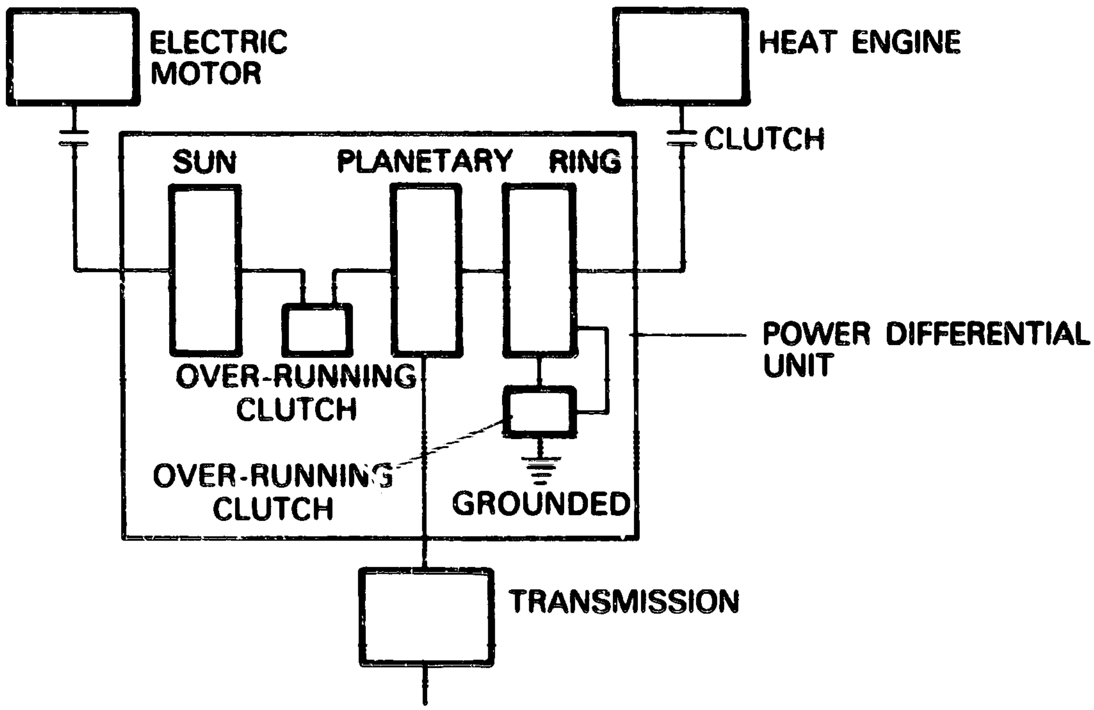
4.9 TORQUE COMBINATION OPTIONS

The two options considered for combining the torque of the electric motor and heat engine are shown in Figure 4.9-1. They are (1) the single-shaft arrangement in which there is a fixed ratio between the motor and engine speeds and (2) the power differential in which the ratio between motor and engine speeds can vary with the torque split between the two prime movers. The relative complexity of the power differential arrangement, which requires the use of two over-running clutches to maintain the heat engine and electric motor in their operating speed ranges for all power train operating modes and torque split ratios, is evident from Figure 4.9-1. The operation of the power differential is discussed in some detail in Appendix B, Vol. I, Sec. 3.5.4.

It was concluded that the added complexity of the power differential and its control could not be justified in terms of possible improved power train efficiency. Hence all the detailed hybrid vehicle simulations were done using the simpler single-shaft approach.



Single-Shaft Torque Combining Arrangements



Schematic of the Power Differential Arrangement

Figure 4.9-1. Torque Combination Options

SECTION 5

DESCRIPTION OF COMPUTER SIMULATIONS

Section 5

DESCRIPTION OF COMPUTER SIMULATIONS

5.1 INTRODUCTION

Computer Simulations, their use, the task on which they were used, and the user/developer are given in this section. As shown in Table 5.1-1, extensive use was made of computer simulations in all tasks of the Phase I Study. Some of the computer programs were developed especially for the hybrid vehicle studies and others were available and in routine use as a vehicle design tool. In this report, only those programs which were developed as part of the Phase I effort are discussed in detail. Some information on the vehicle handling and crash simulation programs is given in Appendix C, Preliminary Design Data Package.

Table 5.1-1

SUMMARY OF THE USE OF COMPUTER SIMULATIONS
IN THE PHASE I STUDY

Program Name	Use	Task	User/Developer
Monte Carlo Trip Length Simulation	Determine daily travel statistics	Mission analysis	Prof. G.E. Smith, University of Michigan
Hybrid Vehicle Design (HYVELD)	Vehicle synthesis, economics and energy-use	Design Trade-off Studies, sensitivity analysis	GE/CRD
Hybrid Vehicle Calculations (HYVEC)	Second-by-second simulation of hybrid vehicle operation on driving cycles	Design trade-off studies, preliminary design	GE/CRD
Linear Range Handling Simulation	Transient handling simulation	Preliminary design	Triad Services
Mass-spring Collision Simulation (SMDYN)	Evaluation of crash worthiness in barrier collision	Preliminary design	Triad Services/ MGA Research

5.2 DAILY TRAVEL STATISTICS

A computer program was developed to analyze daily travel statistics, i.e., the fraction of days and the fraction of annual miles traveled on days for which the total miles traveled was less than a specified value. The calculation procedure used is shown schematically in Figure 5.2-1. The inputs to and outputs from each step of the calculation are indicated in the figure. In essence the daily travel statistics are calculated from input data concerned with annual travel statistics. The key element in the procedure is the Monte Carlo Trip Length Generator which randomly assigns trips of known length to days having a specified number of trips per day. This is done in a manner consistent with the input data on annual travel characteristics. One pass through the procedure for a given set of inputs corresponds to a single car. The procedure is repeated at least 300 times and the results combined to obtain the cummulative probability distributions shown in Figures 5.2-2 and 5.2-3. It should be noted that the procedure described in this section applies only to the random daily travel (e.g., shopping, family business, etc.) and that predictable travel, such as to-and-from work, must be accounted for separately.

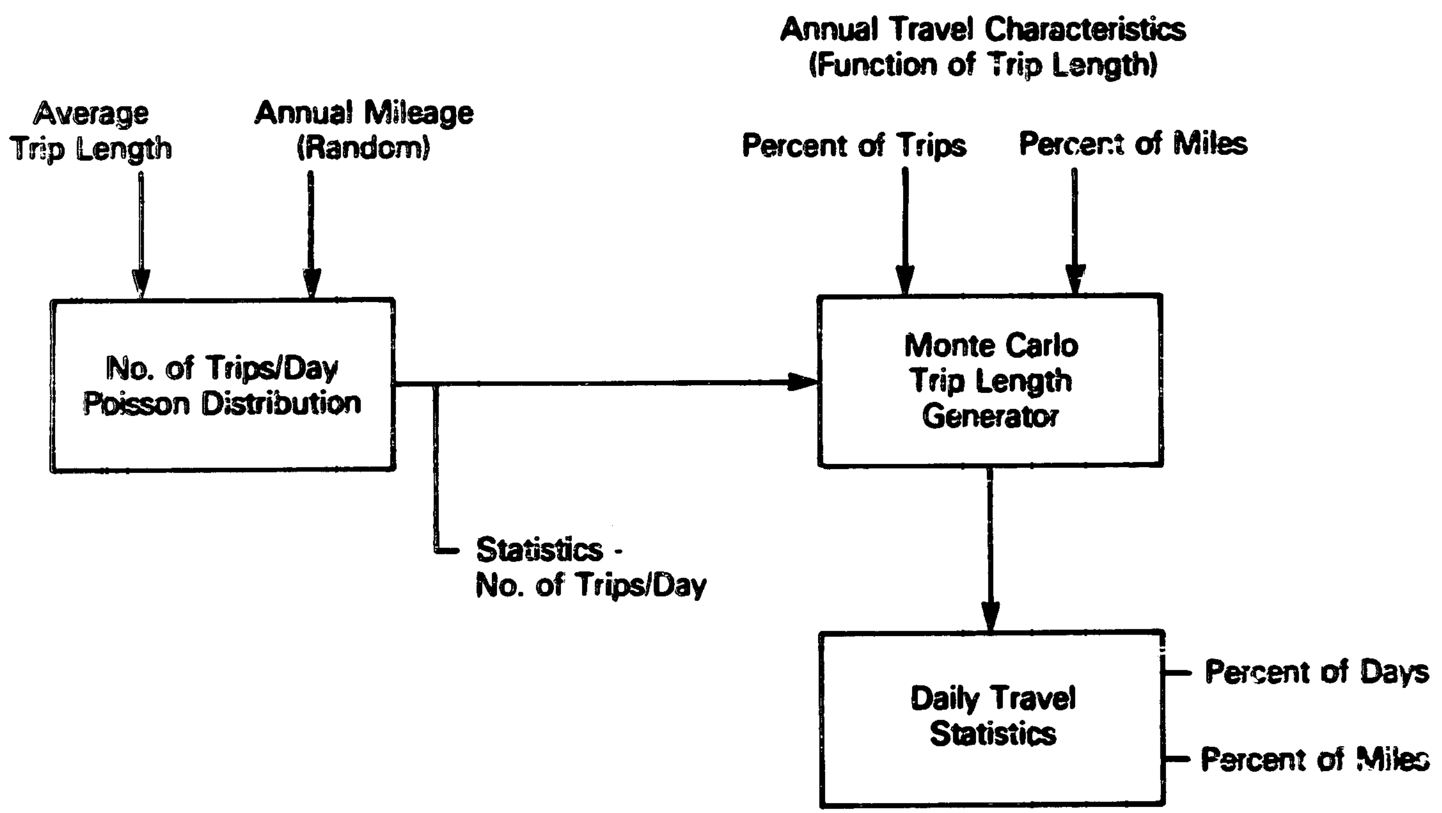


Figure 5.2-1 Calculation of Daily Travel Statistics Using the Monte Carlo Trip Length Generator Program

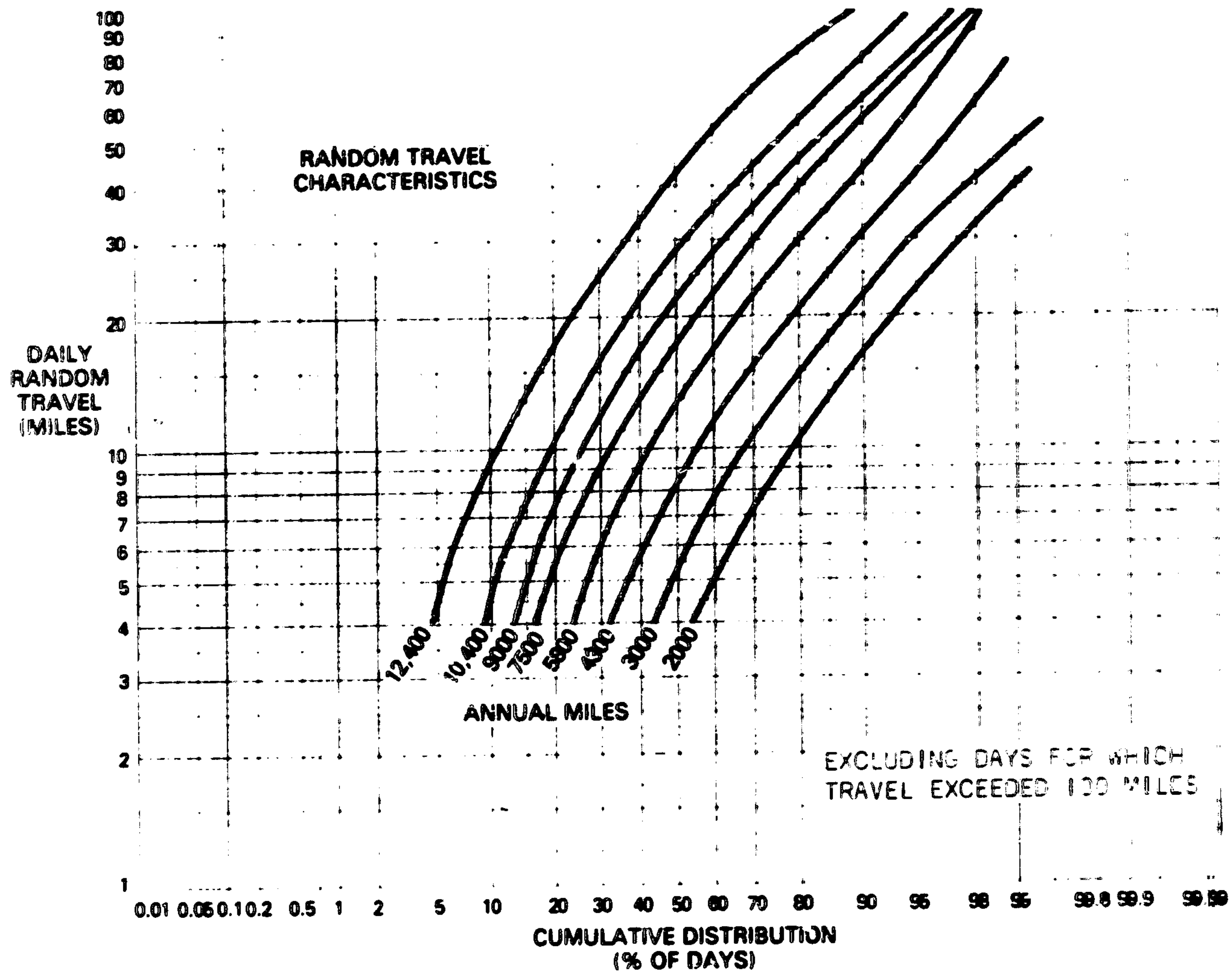


Figure 5.2-2 Daily Random Travel - Percent of Days - as a Function of Annual Miles

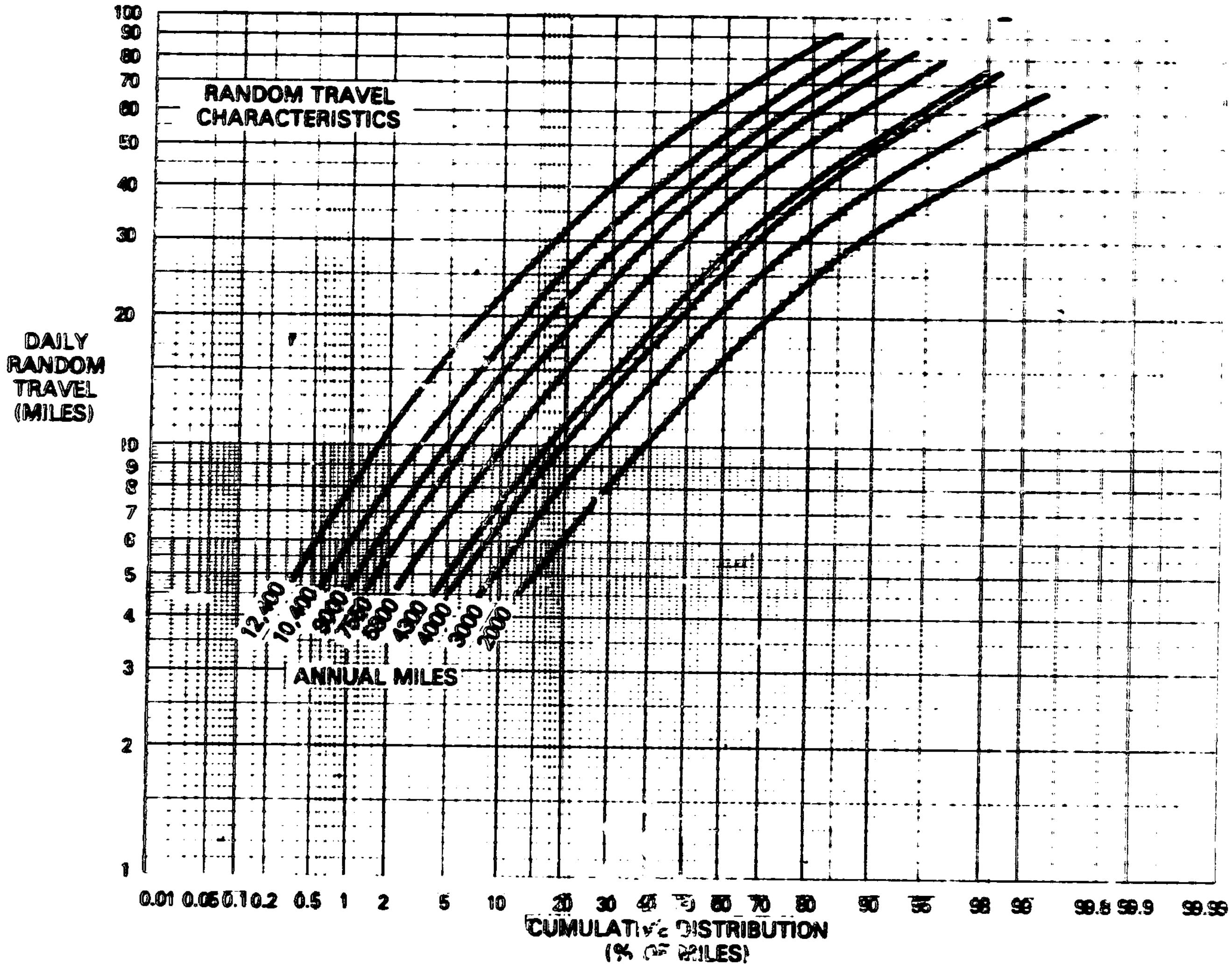


Figure 5.2-3 Daily Random Travel - Percent of Vehicle Miles - as a Function of Annual Miles

5.3 HYBRID VEHICLE DESIGN (HYVELD) CALCULATIONS

The computer program (HYVELD) was developed as part of the Design Trade-off Study. It was used extensively to perform the first step in the screening of the various power train configurations and component combinations. In addition, it was used as the primary tool in the Sensitivity Analysis Studies (Task 4). A complete listing of the program is given in Appendix B, Volume III.

As indicated in Figure 5.3-1, the HYVELD calculation procedure consists of three parts: (1) Vehicle Synthesis, (2) Economics, (3) Energy-use Comparisons. In the Vehicle Synthesis part of the program, the weight and cost of the vehicle and the size and cost of the various power train components are calculated for specified power train configurations and component characteristics. The passenger carrying capacity of the vehicle is set by inputting the appropriate baseline chassis weight, and the use-pattern is specified in terms of annual miles traveled and the fraction of those miles in urban driving. The vehicle performance is given in terms of power-to-weight ratio and electric range. Vehicle synthesis calculations are done sequentially for all-electric, series hybrids, and parallel hybrids with and without secondary energy storage. Calculations are done for a single engine type and a number of battery types (e.g., lead-acid, Ni-Zn, Ni-Fe, Li-S) in each run. The vehicle weight and cost for each power train configuration and component combination is built-up from the Reference ICE Vehicle by subtracting the weight and cost of the conventional power train and adding the weight and cost of the hybrid/electric driveline needed to meet the specified vehicle performance. The effect on the vehicle weight of the added power train weight is accounted for by using a weight propagation factor.

Economics calculations are made for each of the power train combinations treated in the Vehicle Synthesis section of HYVELD. The objectives of the economics calculations are to determine the ownership cost (¢/mi), breakeven gasoline price ($/gal), and net dollars saved or lost ($/yr) for specified unit energy costs, economic conditions (interest, inflation, and discount rates), vehicle life, and maintenance costs (¢/mi). The Reference ICE Vehicle is characterized in terms of its initial cost, fuel economy, life, and maintenance costs. The ownership cost (¢/mi) of the Reference ICE Vehicle is calculated for comparison with that of the hybrid/electric vehicles.

Energy-use calculations are also made for each of the power train combinations. Energy use (electricity and fuel) is calculated separately for urban and highway driving. The results are expressed both in terms of energy used per mile traveled and energy used per year. The fuel and energy used by the Reference ICE Vehicle is also calculated and compared with corresponding values for the hybrid/electric vehicles. Fuel and energy savings are then determined for each power train combination.

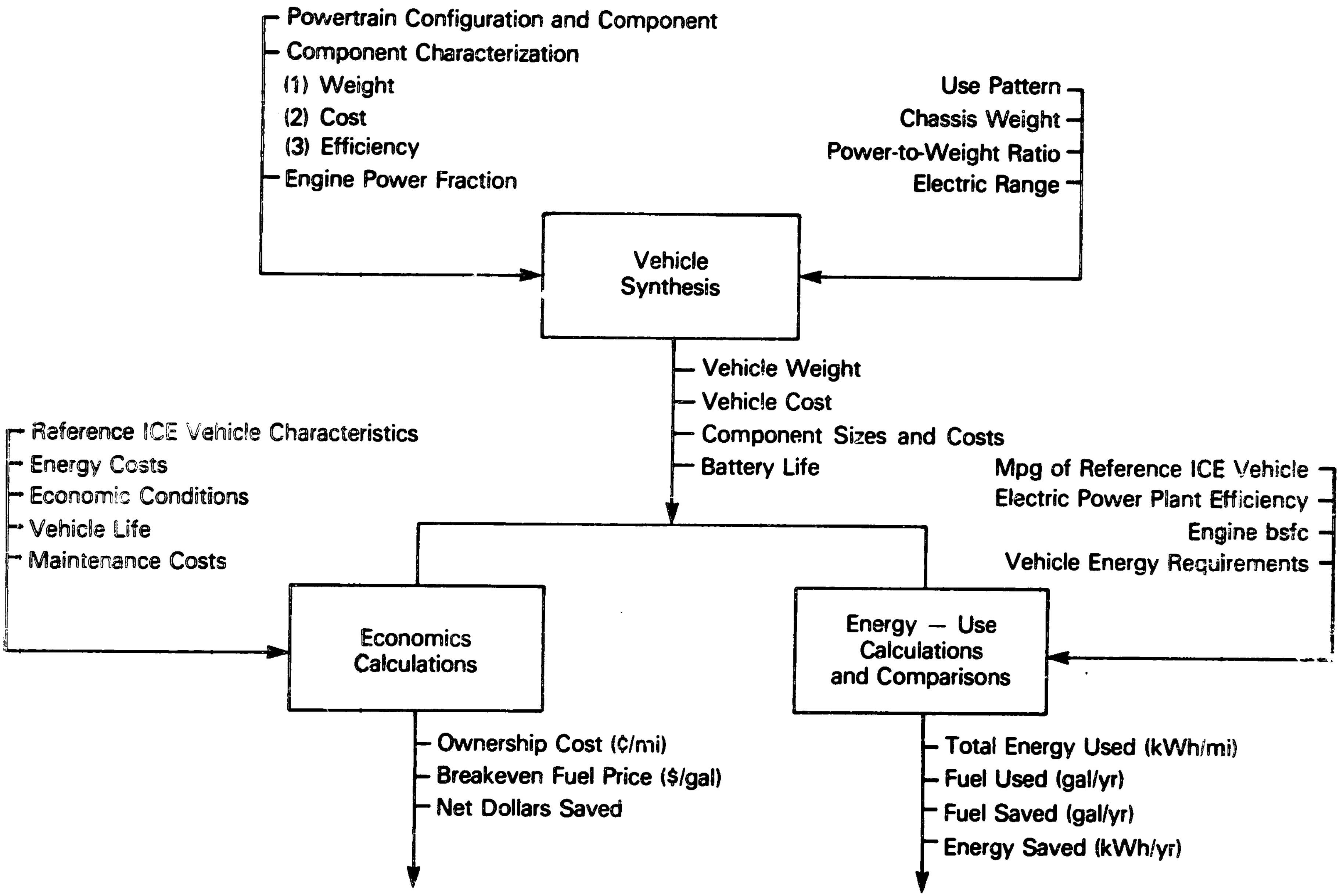


Figure 5.3-1 Schematic of the Hybrid Vehicle Design (HYVELD) Calculation Procedure.

5.4 HYBRID VEHICLE SIMULATION CALCULATION (HYVEC)

The computer program (HYVEC) was developed to simulate second-by-second operation of the hybrid vehicle over urban and highway driving cycles. The program was used extensively in the Design Trade-Off Studies to evaluate the hybrid power train configurations which were identified as the most promising in the first screening. HYVEC was also used in the Preliminary Design Task to update the hybrid vehicle energy-use and performance using refined component characteristics and vehicle weight projections. A complete listing of the program is given in Appendix B, Volume III.

A schematic of the HYVEC calculation procedure is shown in Figure 5.4-1. As indicated in the figure, the calculation for a particular driving cycle is performed starting at the wheels and working from component-to-component through the power train until the fuel and/or electricity needed to drive the vehicle for each increment of time is determined.

Detailed models based on experimental data and analysis are used for each of the power train components. For the electric drive system, motor voltage and current are determined and used as inputs to a battery model which describes the battery in terms of terminal voltage as a function of battery current and state-of-charge. Battery state-of-charge is expressed as the ratio of the AH-used to the cell AH capacity at the time-averaged discharge current. All the electrical power train components are modeled using scaling factors which permit the component sizes (ratings) to be changed without altering the basic inputs to the program. The electric motor is described in terms of the continuous rated power, base speed, and nominal rated voltage and flux. The battery is described in terms of cell AH-rating at the C/3 rate and the number of cells in each battery module (i.e., nominal battery voltage).

The mechanical driveline components, the heat engine and transmission, are modeled in a conventional manner. The heat engine is described by its maximum power and rpm. Fuel consumption and emissions characteristics are input as maps of bsfc and bSem (brake specific emissions - HC, CO, NO_x, particulates) as functions of percent speed and percent of the maximum power at that speed fraction. The multispeed gearbox transmissions are described in terms of the gear ratio and efficiency in the various gears, and the pumping losses if the gearbox is hydraulically shifted. The steel-belt CVT is described in terms of the maximum reduction speed ratio and the maximum overdrive speed ratio. Friction and pumping losses are combined into a single, speed-dependent loss term for the CVT.

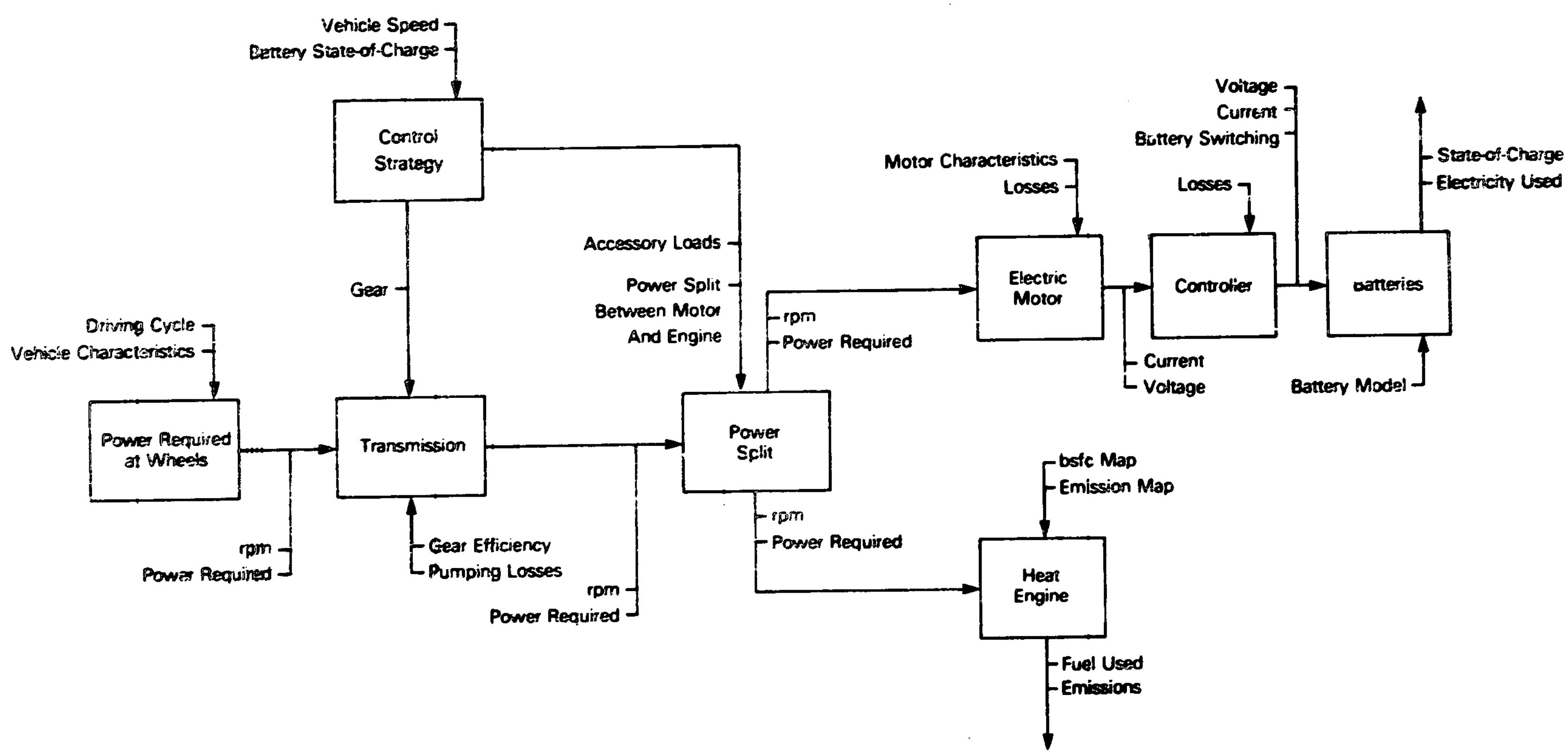


Figure 5.4-1 Schematic of the Hybrid Vehicle Simulation Calculation (HYVEC).

The control strategy for operating the hybrid power train is described in HYVEC by a series of statements which specify under what conditions the engine is on, what fraction of the power required is supplied by the electric motor, when the gearbox should be shifted or the battery charged, how the accessory loads should be met, etc. Development of the control strategy for the hybrid vehicle was a key part of the Phase I study, and the HYVEC program was an important tool in that development. The details of the control strategy evolved were discussed in Section 3.2.1.6.

The HYVEC program was also used to calculate the maximum effort acceleration performance of the hybrid vehicle. In those calculations, both the heat engine and electric motor are operated at the maximum power (or torque) attainable from them at each vehicle speed. The gear shifting strategy is such that the motor and engine are permitted to operate much nearer their maximum rpm than in usual driving. Particularly for the heat engine, this increases the power available at moderate vehicle speeds. The maximum power attainable from the electric drive system depends on the state-of-charge of the battery. As the battery charge is depleted, the voltage droop of the battery increases at high currents and the maximum power the battery can provide becomes smaller. Maximum effort acceleration calculations at specified levels of battery state-of-charge can be made with HYVEC.

Section 6

ECONOMIC ANALYSES

Section 6

ECONOMIC ANALYSES

6.1 INTRODUCTION

Initial and ownership costs of the hybrid vehicle relative to the Reference ICE Vehicle (1985 model) are important factors in determining the marketability of the hybrid vehicle. Hence considerable attention was given in the Phase I study to economic analyses and to the calculation of various component and vehicle cost factors. Almost all the economic calculations were done using the HYVELD program. In the Design Trade-Off Studies (Task 2), the initial and ownership costs were calculated for each of the power train configurations and component combinations evaluated. A major portion of the Sensitivity Analysis Study (Task 4) involved determining the effect of variations in component costs, use-pattern, economic conditions, and energy costs on the initial and ownership costs of a parallel hybrid vehicle similar to that designed in Task 3.

The results of the Task 2 and Task 4 studies, including the economic calculations, are presented in detail in Appendices B and D. Hence, in this report, the methods used in the economic analyses are emphasized and the results obtained are considered only in general terms. In particular, quantitative results for a wide range of economic parameters are given in Appendix D, Section 4.

The discussion of the economic analyses is divided into three parts: (1) Determination of component costs, (2) calculation of the initial vehicle cost, and (3) calculation of the ownership cost of the vehicle. The approaches discussed form the basis of the economic calculations done using HYVELD.

6.2 METHODS OF ANALYSIS

6.2.1 DETERMINATION OF COMPONENT COSTS

The costs of the components in the hybrid power train were calculated using specific cost values ($/kW or $/kWh) assigned to each component. The specific cost values were determined as part of the Design Trade-Off Study.* For the electric motor and power electronics, including the microcomputer, the specific cost values used were based on the results of a cost study done by GE as part of the GE/DOE Near-Term Electric Vehicle Program. The specific costs of the heat engine and transmission were based on published and unpublished results of the Pioneer Engineering and Manufacturing Company for conventional ICE automobiles. For the batteries, the specific cost ($/kWh) of the various types was taken from the published cost goals for the DOE/ANL battery programs.

The cost values determined were treated in HYVELD as the OEM costs to the hybrid vehicle manufacturer in production rates comparable to those of the conventional automobile (i.e., components were mass produced by a number of suppliers for a large market).

6.2.2 CALCULATION OF THE INITIAL COST

The initial cost of the hybrid vehicle was calculated from that of the Reference ICE Vehicle (1978 model) by first subtracting the cost of the conventional driveline and then adding the cost of the hybrid power train and the additional weight needed to support it. For a particular hybrid vehicle design, the power train components were sized (i.e., kW or kWh rating of the components specified) in the Vehicle Synthesis part of the HYVELD program, and the cost of each component was found by simply multiplying the component rating (kW) times its specific cost ($/kW). The added weight was determined by using a weight propagation factor and the associated cost was calculated on the basis of a fixed average cost per pound for standard automotive components and structure.

The initial cost calculated is the selling price to the consumer as indicated by the vehicle's sticker price. A factor of 1.3 was assumed between the OEM cost and vehicle sticker price. This factor accounts for dealer markup and other marketing expenses. The selling price of the Near-Term Hybrid Vehicle calculated using OEM component costs and a markup factor of 1.3 agrees well with that calculated starting from component manufacturing costs and a multiplication factor of 2.0 as suggested in the Electric and Hybrid Vehicle Cost Handbook prepared by JPL.

*Appendix B, Volume I, Section 3.

6.2.3 CALCULATION OF THE OWNERSHIP COST

Determination of the ownership cost (¢/mi) of the hybrid vehicle is a rather complex procedure because ownership cost is made up of a number of elements including

- Depreciation
- Battery replacement cost
- Fuel and electricity costs
- Routine maintenance and repair costs
- Miscellaneous (registration, insurance, etc.)

Some of these elements depend, in a complex manner, on general economic conditions, vehicle lifetime, and vehicle use pattern. The ownership cost of the Reference ICE Vehicle was calculated in a manner consistent with that used for the hybrid vehicle.

The method used in the HYVELD program to calculate each of the elements in the total ownership cost is discussed in the following paragraphs.

6.2.3.1 Depreciation

The annual cost of depreciation to the vehicle owner was calculated using the present worth/capital-recovery factor approach corrected for the front-end loaded depreciation typical of automobiles. It was assumed that the hybrid and conventional ICE vehicles were both bought new and sold at the end of the four-year finance period by their first owners. The difference between the original present worth and the depreciated present worth after four years was evenly distributed over the four-year period to obtain the annual cost of depreciation to the first owner. The nonlinear depreciation scheme used is often referred to as the "reverse sum of the digits" approach, which can be expressed analytically as

$$\frac{\text{Resale Value}}{\text{Original Value}} = \frac{\sum_{k=0}^{N_F-1} (N_V-k)}{\sum_{k=1}^{N_V} k}$$

where N_V is the lifetime of the vehicle and N_F is the finance period of the first owner. The nonlinear depreciation factor is then

$$\text{NLLF} = \frac{2N_V - N_F + 1}{N_V + 1}$$

The annual cost of depreciation (ACD) for the vehicle can be written as

$$ACD = (NLLF)(FF)(FRCV)(VIC)$$

where

VIC = Vehicle initial cost (less batteries)

FF = Finance factor $= \dfrac{NF \quad IRE}{1 - (1 + IRE)^{-NF}}$

$FRCV$ = Fixed recovery factor

$$= \frac{DR - IF/1 + IF}{1 - \left(\frac{1 + DR}{1 + IF}\right)^{-NV}}$$

The economic condition factors used are defined as follows:

IRE = Effective interest rate = $(1 - Tx)IR$

Tx = Tax rate

IR = Interest rate

DR = Discount rate

IF = Inflation rate

The annual depreciation cost was then divided by the annual mileage to obtain the contribution of depreciation to the ownership cost. The same expressions apply to both the hybrid and conventional vehicles except that different values were used for vehicle initial cost and lifetime (i.e., VIC and N_V).

6.2.3.2 Battery Replacement Cost

The annualized replacement cost of the batteries (ACB) was calculated using the present worth/capital recovery factor approach. Hence

$$ACB = (FF)(FRCB)(BC)$$

where

BC = Battery cost (less salvage value)

FF = Finance factor

$FRCB$ = Fixed recovery factor

$$= \frac{DR - IF}{1 + IF} \Big/ 1 - \left(\frac{1 + DR}{1 + IF}\right)^{-Y_L}$$

Y_L = Battery Life (years)

The battery life was determined by HYVELD from input values of battery cycle life and associated depth of discharge for that cycle life and calculated battery weight and electric energy use (kWh/mi). The annualized battery replacement cost was then divided by the annual mileage to obtain the contribution of battery replacement to the ownership cost.

.3.3 Fuel and Electricity Costs

The fuel (gasoline) and electricity costs were calculated by HYVELD separately for urban and highway driving. For each type of driving, the energy required per mile at the wheels to drive the vehicle was determined based on the calculated total vehicle weight and input values of the specific energy requirement (kWh/ton-mi). The fraction of the driveshaft energy that is provided by the heat engine drive system was given by an input parameter which was determined from detailed HYVEC simulations. This fraction depends on the design electric range of the hybrid vehicle and its use pattern. The remainder of the energy required by the vehicle comes from the energy stored in the battery.

The electrical energy required (kWh) from the plug to recharge the batteries depends on the electrical energy needed to power the hybrid vehicle and the charge/discharge efficiency of the battery. The fuel used by the heat engine depends on the energy provided at the driveshaft from the engine and the average bsfc (lb/bhp/hr) of the engine over the urban and highway cycles. Average values of battery charge/discharge efficiency and engine bsfc's were used in the HYVELD calculations.

The fuel (gallons) and electricity (kWh) used in urban and highway driving were calculated as indicated for specified annual miles traveled and fraction of miles in urban driving. The annual fuel and electricity costs then follow directly from the assumed unit costs of gasoline ($/gal) and electricity (¢/kWh). The total energy cost is the sum of the fuel and energy costs, and the contribution of energy cost to ownership cost was found by simply dividing the total energy cost by annual miles traveled.

The fuel costs (¢/mi) for the Reference ICE Vehicle were calculated from input values of miles per gallon for urban and highway driving.

6.2.3.4 Routine Maintenance and Repair Costs

All maintenance and repair costs, with the exception of battery replacement, were included in the category of routine

maintenance and repair. The maintenance costs of the hybrid vehicle (MCHV) were referenced to those of the conventional ICE vehicle (MCCV) as

$$MCHV = (1 - MIFHV)MCCV$$

where MIFHV is the maintenance improvement factor for the hybrid vehicle. The maintenance/repair cost of the conventional vehicle for the first owner (first four years of operation) was taken to be 3¢/mi in 1978 dollars. It is felt that after the hybrid vehicle is highly developed and road-tested, its maintenance costs will be less than those of the ICE vehicle because of the inherent low maintenance required of the electric drive system components and the fact that the heat engine is used for only a fraction of the vehicle miles driven each year. A nominal maintenance improvement factor of 25% was used for the hybrid vehicle.

6.2.3.5 Miscellaneous Costs

The miscellaneous cost category included the costs of vehicle registration and insurance - both fixed costs independent of miles driven. These costs were simply pro-rated over the annual miles traveled.

6.3 MAJOR FINDINGS

Extensive calculations were made in Tasks 2 and 4 dealing with the economic attractiveness of the hybrid vehicle relative to the Reference ICE Vehicle. The results of those calculations for various hybrid vehicle designs are discussed in detail in the final reports of those tasks (Appendices B and D). In this section, the major findings of the economic studies will be noted as they relate in a general way to the Phase I study.

(1) The initial cost (sticker price) of the hybrid vehicle is $1500 to $2000 higher than that of the Reference ICE Vehicle.

(2) The ownership cost (¢/mi) of the hybrid vehicle is comparable to that of the Reference ICE Vehicle for a gasoline price of $1.0/gal. At that fuel price, whether the ownership cost of the hybrid is slightly higher or lower depends on the relative vehicle lifetimes and maintenance costs.

(3) At a fuel price of $2/gal, the ownership cost of the hybrid vehicle is significantly lower (3 - 4¢/mi) than that of the Reference ICE Vehicle, even if the lifetime and maintenance cost of the two vehicles are the same. Increases in electricity cost (e.g., doubling the cost from 4.2 to 8.4¢/kWh) have only a minor effect (about 0.5¢/mi) on the relative ownership costs of the hybrid and ICE vehicles.

(4) The economic attractiveness, and thus the market penetration, of the hybrid vehicle is not strongly dependent on its use pattern - that is, annual mileage and fraction of miles in urban driving.

Section 7

MAINTENANCE AND RELIABILITY CONSIDERATIONS

Section 7

MAINTENANCE AND RELIABILITY CONSIDERATIONS

7.1 INTRODUCTION

A discussion of maintenance and reliability is presented in this section. The discussion considers factors relative to the hybrid vehicle, the Reference ICE Vehicle, and an all-electric vehicle. Additional information regarding maintenance and reliability of the hybrid vehicle is given in Appendix C, Section 4.8.

7.2 MAINTENANCE CONSIDERATIONS

Maintenance of the hybrid vehicle entails attention to the same items as maintenance of the Reference ICE Vehicle. In addition, the electric drive system of the hybrid vehicle must also be maintained. Considerable thought has been given to the maintenance of the elctric drive system as part of the DOE/GE Near-term Electric Vehicle Program. Table 7.2-1, taken from the Operation and Maintenance Manual prepared for the DOE/GE Electric Car, lists maintenance actions and frequency for the electric driveline. Most of those items would also be required for the hybrid vehicle. Routine maintenance and tune-ups for the heat engine should be less frequent for the hybrid vehicle, because the engine would be used only a fraction of the driving time (i.e., it would take longer in calendar time to accumulate a fixed number of equivalent miles or operating hours). The engine oil and coolant would have to be selected such that they could function longer between changes. One would expect that the brakes on the hybrid vehicle would last more vehicle miles than the brakes on the Reference ICE Vehicle because regenerative braking supplies much of the stopping torque in stop-and-go urban driving. After the electric motor and electronics are fully developed and road-tested for millions of miles, it is reasonable to expect that they will have long life and a minimum of routine maintenance. The batteries will, of course, require continuing attention if they are to have a long life, but most of that maintenance can be done by the car owner if the battery charging (including equalization charging) and watering systems are well designed.

In the calculations of ownership cost it was assumed that paid-for maintenance of the hybrid vehicle would be 25% less than for the Reference ICE Vehicle after the hybrid power train is well developed and road-tested. This assumption is primarily based on the less frequent need for engine maintenance/tune-ups and the expectancy that the electric motor/electronics are relatively maintenance free. It was also assumed that with proper design of the nonpropulsion components,* the effective lifetime (miles or years) of the hybrid vehicle could be extended beyond

*Additional chassis and running gear cost (5%) has been included for the hybrid vehicle.

Table 7.2-1

MAINTENANCE FOR DOE/GE NEAR-TERM ELECTRIC VEHICLE

Maintenance Item	Maintenance Action	Frequency
Propulsion Batteries	Perform watering procedure	Every 2 months
	Check operation of watering/vent valves	Every 2 months
	Check watering/venting tubing for evidence of cracks, pinching, looseness on fitting	Every 6 months and when battery compartment removed from vehicle
	Perform equalization procedure	Once every 7 normal charges
	Drop battery tray and clean battery tray of debris	Every 6 months
	Check specific gravities or open-circuit voltage	Every 6 months
Flame Arresters	Inspect and clean	Every 6 months
	Replace Flame Arresters	Every 2 years
Watering Tubing	Inspect and move or replace flattened section of off-board watering tubing	Every 12 months
AC Power Cord	Inspect for frayed or broken wires	Every 6 months
108 Volt DC System	Validate isolation of 108 dc system from chassis	Every 2 months
Ground-Fault Current Interrupter	Check normal trip mechanism via test button	Every 6 months
High-Amperage Heavy Cabling	Inspect cable from battery to OD switch to PCU and motor	Every 6 months
Drive Motor Brushes, Commutator Cleanliness	Inspect	Every 6 months
Drive Motor Brushes	Replace	Every 2 years

that of the Reference ICE Vehicle because of the expected longer calendar life of the heat engine and the longevity of the electric drive components. A hybrid vehicle life of 12 years or 120,000 miles was used in the cost calculations. It would, of course, be necessary to replace the battery pack several times during the hybrid vehicle lifetime, but that cost is included separate from the routine or repair maintenance costs.

7.3 RELIABILITY CONSIDERATIONS

The reliability of the hybrid vehicle should be greater than that of the Reference ICE Vehicle, because the hybrid vehicle has two, rather than one, drive systems. Both systems would have to be inoperable for the vehicle to be stranded or totally unusable. The hybrid power train is designed such that the vehicle can operate on either of the drive systems alone, but at reduced performance.

It is difficult to assess quantitatively the vehicle maintenance and reliability factors (P14 through P16). If the probability of a failure for each of the components in the power train is approximately the same, then it would be expected that system failures with the hybrid vehicle would be significantly more frequent than those with the Reference ICE Vehicle. Clearly, this cannot be permitted to be the case, or the hybrid vehicle could not be marketed in competition with the ICE vehicle. Hence a design goal for the hybrid vehicle (fully developed and tested) must be to maintain power train and vehicle failures to the same or lower frequency than that for the conventional ICE vehicle. Engine failures would be expected to be less frequent with the hybrid vehicle, because the engine is used less of the time. In addition, suitably designed electrical/electronic components have less frequent failures than mechanical components. Friction brake failures for the hybrid vehicle would be less frequent than for the conventional vehicle because the friction brakes are used less. Major repair of the electric drive system is expected to require less time than that of the engine, because the electrical components are smaller and lighter and it is feasible to replace the faulty component with a new or rebuilt one as is done with alternators, starter motors, and electronic ignition systems in conventional vehicles. In addition, it seems less difficult to engineer self-diagnostic capability into the electric drive system than into the engine system. Hence, it appears reasonable that repair of the electric drive system will take less time and exhibit less variability from case to case than repair of the conventional ICE vehicle. It is, of course, assumed that the power train is assembled such that suitable access is provided to the electric drive components and electronics. The factors P14 through P16 are estimated qualitatively in Table 7.3-1 in relation to the Reference ICE Vehicle only after the hybrid vehicle is well-developed and road-tested. Hence the maintenance/reliability factors are intended only as long-term design goals of the hybrid vehicle development program.

Table 7.3-1

VEHICLE MAINTENANCE AND RELIABILITY FACTORS*

Factor	Estimate Relative to ICE Vehicle
P14 Reliability	
P14.1 Mean usage between failures - power train	same as or less frequent failures
P14.2 Mean usage between failures - friction brakes	less frequent failures
P14.3 Mean usage between failures - vehicle	same as or less frequent failures
P15 Maintainability	
P15.1 Time to repair - mean	smaller
P15.2 Time to repair - variance	smaller
P16 Availability	
Minimum expected utilization rate defined as time in service divided by the sum of time in service and time under repair	higher

*Compared with an ICE vehicle after the hybrid vehicle is well developed and road-tested

Section 8

DESIGN FOR CRASH SAFETY

Section 8

DESIGN FOR CRASH SAFETY

8.1 INTRODUCTION

A discussion of the crashworthiness of the hybrid vehicle is given in this section. A methodology is developed which establishes a correlation between the hybrid vehicle design and the crashworthiness already established for the Reference ICE Vehicle (1979 Chevrolet Malibu).

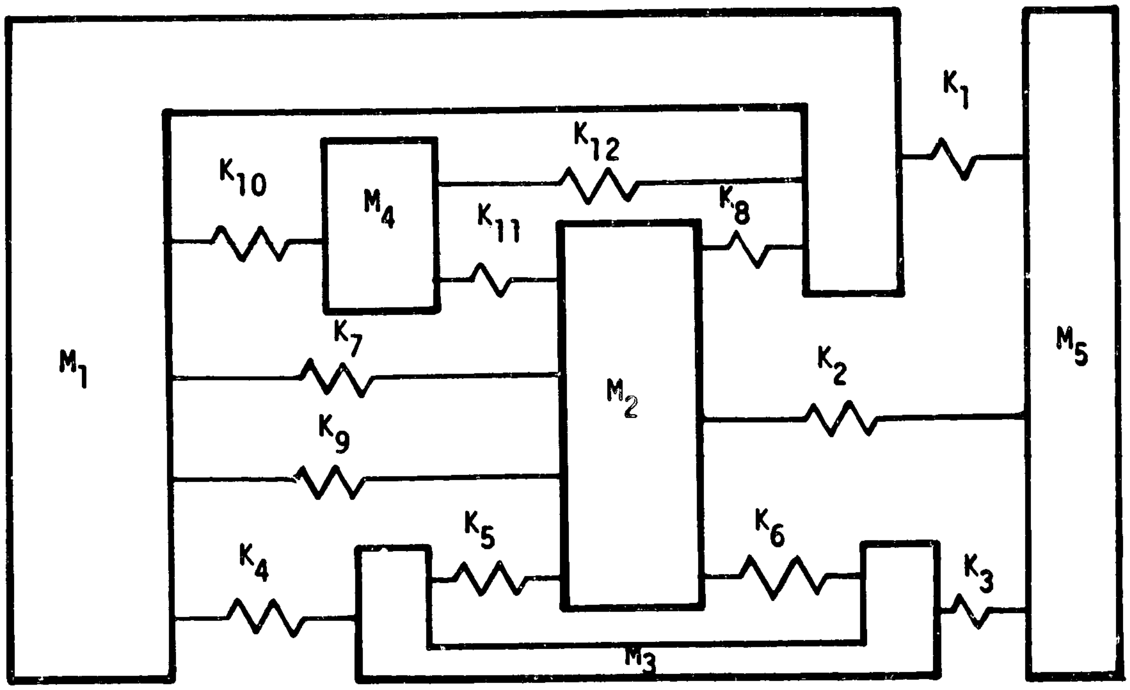
8.2 METHODOLOGY FOR CRASHWORTHINESS EVALUATION

In order to provide a preliminary assessment of the crashworthiness of the hybrid vehicle's frontal structure and drive component placement, a computer study was conducted. Utilizing the preliminary design configuration, a series of vehicle collision simulations was made to evaluate the vehicle crash environment for a 30 mi/hr frontal barrier impact. The computer study was done using the lumped mass vehicle collision simulation program (SMDYN). A schematic of the forward structure and components used for the computer simulations is shown in Figure 8.2-1. As indicated in Figure 8.2-2 both the front and underbody structures of the hybrid vehicle will be redesigned in order to support the added weight and crash loads as compared with the stock Malibu.

The methodology used to evaluate the crashworthiness of the hybrid design was based on the fact that the hybrid's passenger compartment is identical to that of the 1978 Chevrolet Malibu and the assumption that occupant survivability in the hybrid configuration would occur if the hybrid's crash environment was found to be comparable to that of the Malibu. Compliance test crash data was obtained for a 1978 GM A-Body car. That data provided the basis of comparison for evaluating the proposed hybrid configurations. Since static crush data was not available for the Malibu structure, data from similar vehicles was used in the SMDYN model to attempt to duplicate on the computer the vehicle collision performance of the Malibu. Modifications were made to the crush data until a match was achieved between simulation results and the known Malibu deceleration pulse.

After the base vehicle (Malibu) simulation was completed, a series of calculations was made to study the following hybrid vehicle factors:

- Longitudinal and transverse heat engine package without a battery pack
- Both engine configurations with battery packs installed behind the heat engine



M_1	-	body
M_2	-	engine/drive system
M_3	-	cross member/unsprung mass
M_4	-	battery
M_5	-	barrier
K_1	-	upper sheet metal
K_2	-	radiator/engine front
K_3	-	front frame rails
K_4	-	rear frame rails
K_5	-	engine mount (rearward)
K_6	-	engine mount (forward)
K_7	-	transmission (rearward)
K_8	-	transmission mount (forward)
K_9	-	drive system/firewall
K_{10}	-	battery/firewall
K_{11}	-	engine/battery
K_{12}	-	battery containment structure

Figure 8.2-1. Schematic of the Hybrid Vehicle Forward Structure and Components for Crash Simulation

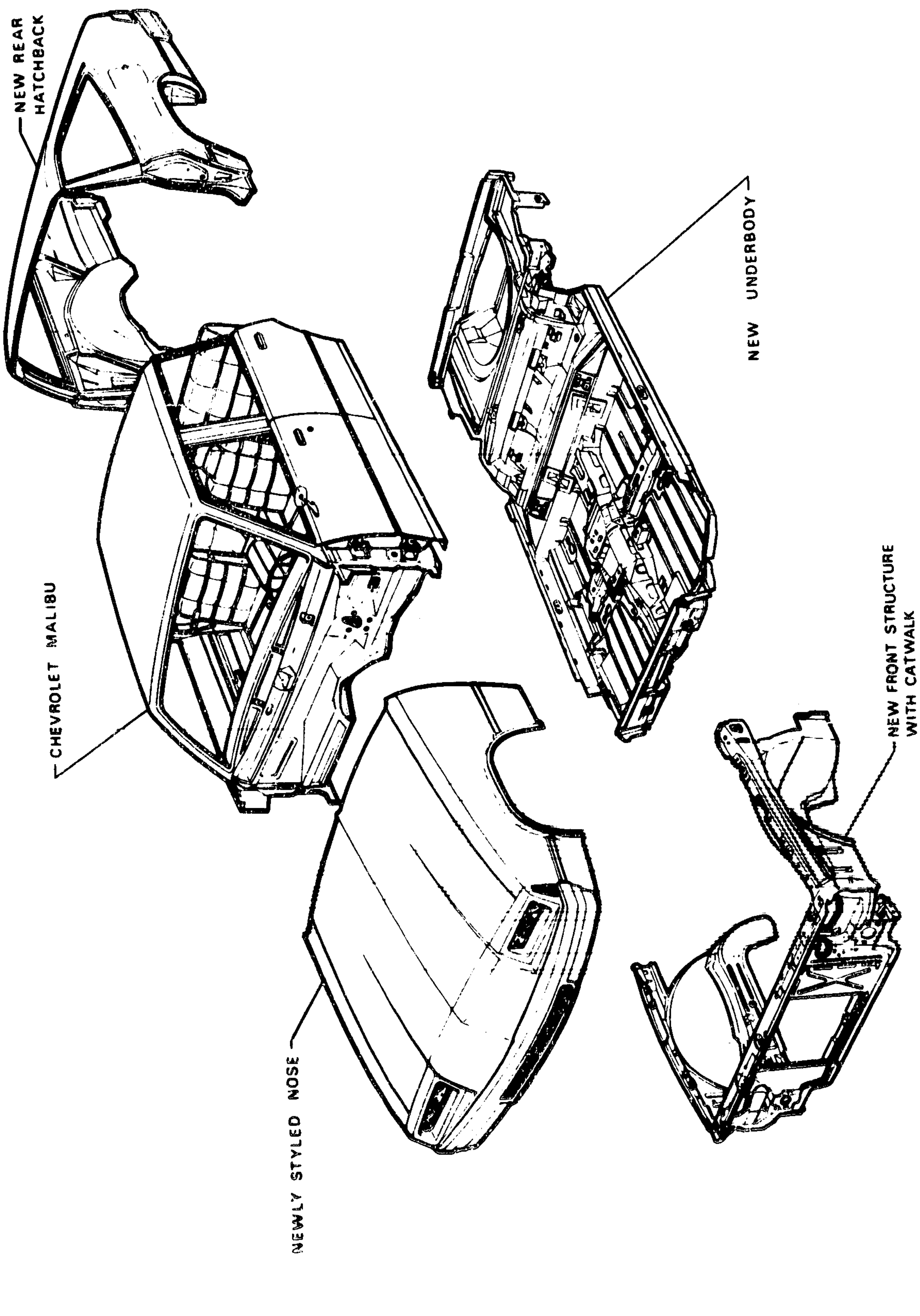


Figure 8.2-2. Hybrid Vehicle Body Structure, Exploded View

- Standard and soft battery pack crush characteristics

- Structural component changes

- Variations in vehicle height

The cases calculated and the results obtained are summarized in Table 8.2-1. The details of the crash simulation studies are given in Appendix C, Preliminary Design Data Package.

Table 8.2-1

SUMMARY OF CRASH SIMULATION RESULTS

RUN NO.	Configuration	Maximum Deceleration (G)	Maximum Crush (in.)	Drive System Intrusion (in.)	Battery Intrusion (in.)
1	Conventional Drive	32.35	28.76	4.38	-------
2	LDS Hybrid - No Batteries	24.67	25.82	16.64	-------
3	TDS Hybrid - No Batteries	23.01	28.99	10.87	-------
4	LDS Hybrid - Standard Batteries	26.72	26.90	16.9	7.46
5	TDS Hybrid - Standard Batteries	26.09	30.88	12.17	4.97
6	LDS Hybrid - Soft Batteries	24.81	27.00	17.82	3.45
7	TDS Hybrid - Soft Batteries	24.01	30.94	12.18	1.62
8	Light LDS Hybrid	30.90	23.81	14.18	4.46
9	Light TDS Hybrid	28.83	27.68	8.86	1.43
10	TDS Hybrid - Strengthened Frame	25.53	29.96	10.94	3.65
11	Light LDS Hybrid Strengthened Frame	33.97	22.82	14.21	2.02
12	Light LDS Hybrid Strengthened Frame	28.42	26.27	7.66	0.2
13	Light TDS Hybrid Strengthened Structure	26.58	24.80	6.61	0.0

8.3 CRASHWORTHINESS ANALYSIS CONCLUSIONS

The following conclusions were derived from the crash simulation study:

(1) The Transverse Drive System (TDS) package shows much greater promise of affording crash protection comparable to that of the conventional Malibu than does the Longitudinal Drive System (LDS) as shown in Figure 8.3-1 and 8.3-2. The LDS could afford similar levels of protection only if more structural crush space were available under the hood.

(2) For both drive system configurations, the maximum intrusion into the passenger compartment occurred in the tunnel area as a result of the movement of the heat engine and associated drive components. This area of the body structure should receive a high level of emphasis during Phase II.

(3) Increasing the structural resistance (but utilizing values within the state of the art of automotive technology) reduces passenger compartment intrusion without significantly affecting the peak deceleration levels of the TDS Hybrid System.

(4) Battery pack intrusion into the passenger compartment should not be a serious problem. The TDS layout can achieve a desired objective of preventing such intrusion. However, further test information is required for the interaction between the transverse heat engine and battery pack.

(5) Although occupant response was not addressed directly in the study, it seems likely that a hybrid vehicle design which paid careful attention to crashworthiness would satisfy FMVSS 208 injury criteria for fully restrained occupants. This conclusion is based on the similar passenger compartment decelerations for the Chevrolet Malibu and the TDS strengthened structure and on the occupant injury levels recorded in the GM A-Body tests.

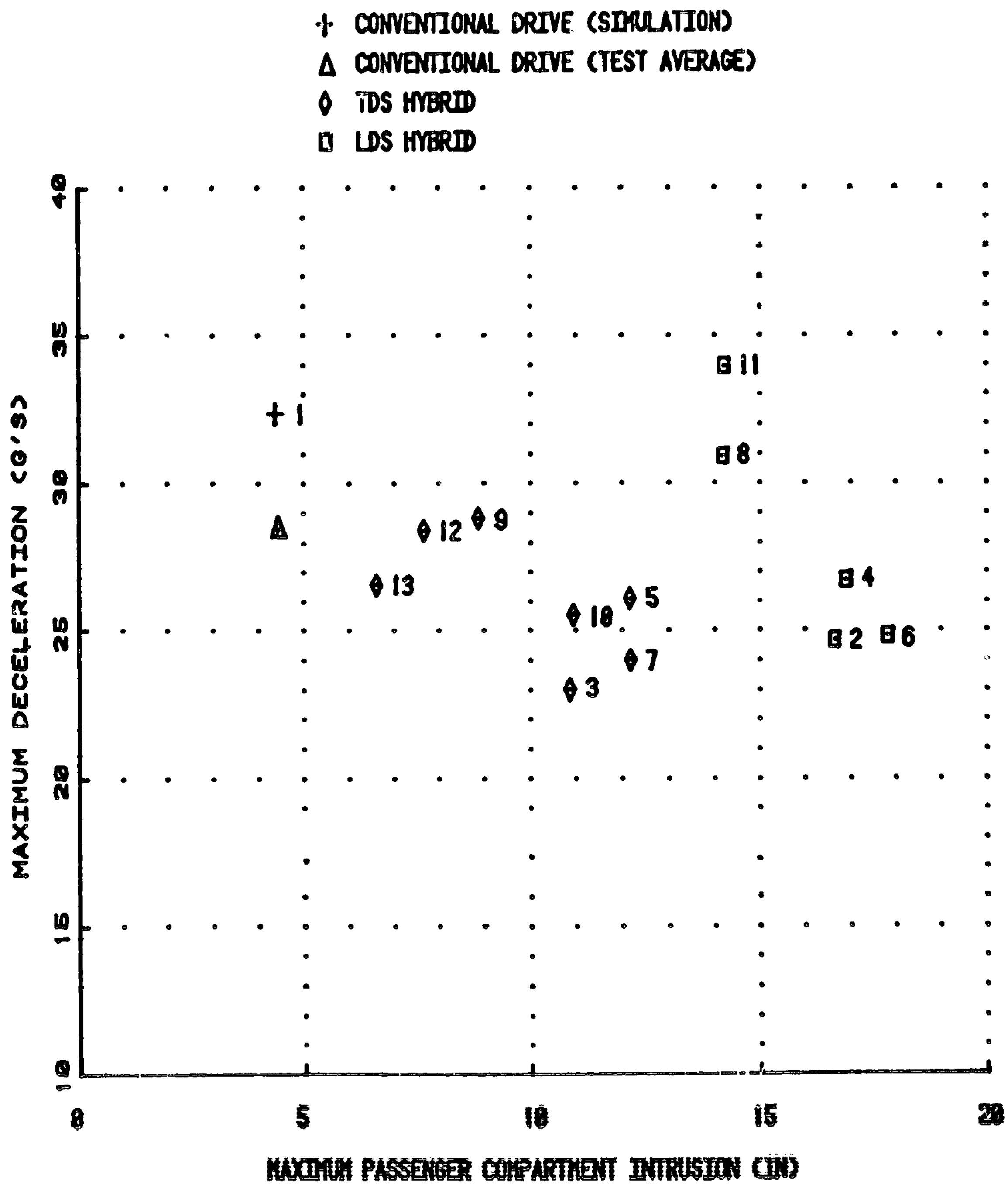


Figure 8.3-1. Maximum Deceleration as a Function of Maximum Intrusion (Refer to Table 8.2-1 for Run Identification)

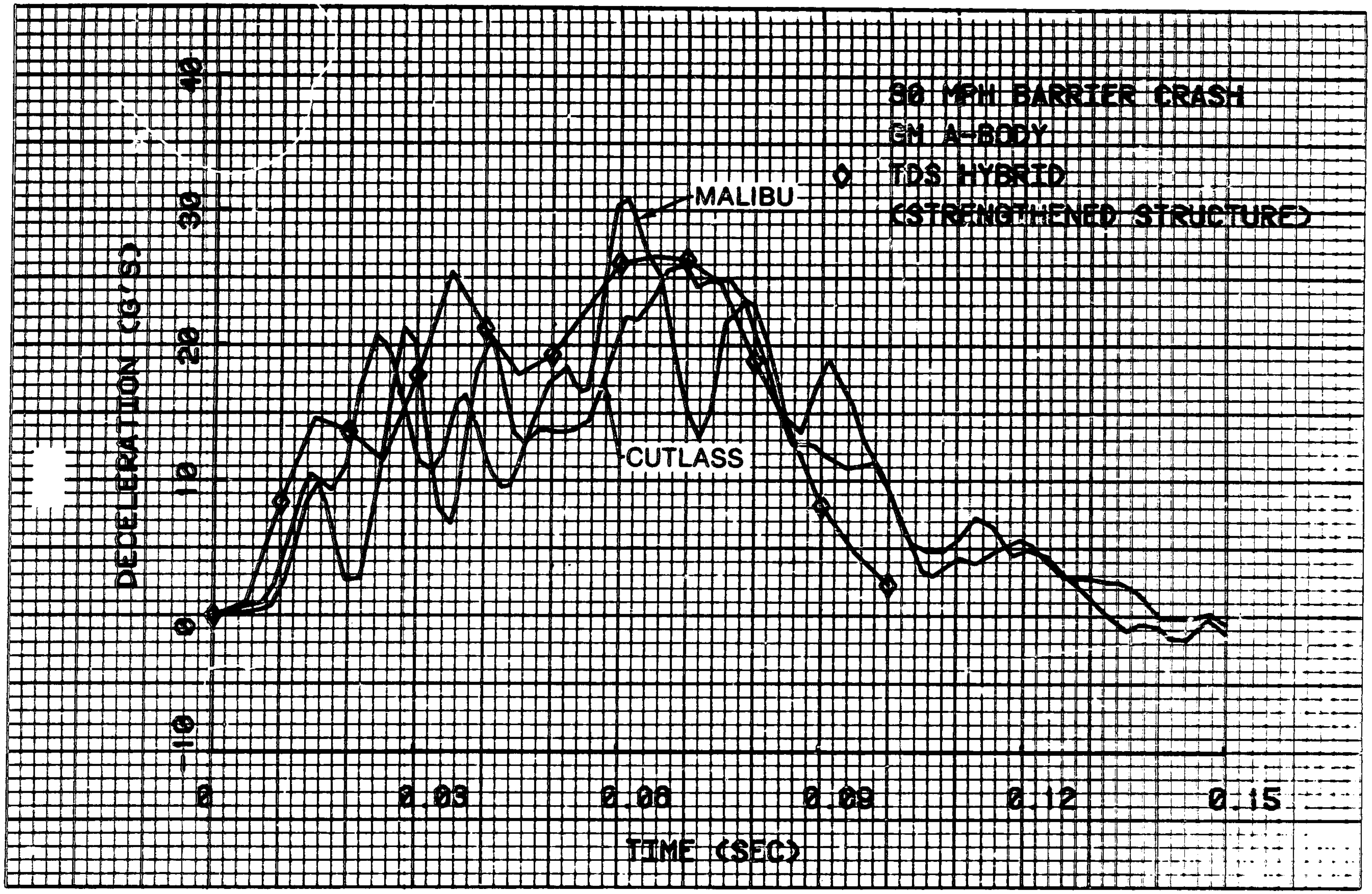


Figure 8.3-2. Comparison of the Transverse Hybrid Driveline and Stock Malibu Crash Test Performance

Section 9

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Section 9

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